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CHEMICAL-PHYSICAL ASPECTS OF DEEP TRICKLING FILTERS

Frederick J. Burgess, et al

Oregon State University

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ASPECTS OF DEEP TRICKLING FILTERS

U.S. Public Health Service
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Investigators

Fredrick J. Burgess
Professor of Civil Engineering
Department of Civil Engineering

Fred Merryfield
Professor of Sanitary Engineering
Department of Civil Engineering

Cameron M. Gilmour
Professor of Bacteriology
Department of Microbiology

Donald C. Phillips
Associate Professor of Sanitary Engineering
Department of Civil Engineering

Oregon State University
Engineering Experiment Station
Corvallis, Oregon

September 1, 1964

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PERSONNEL ASSOCIATED WITH THIS PROJECT

Name	Position with project	Now employed by
Fredrick J. Burgess	Prof of Civil Engineering Asst to the Dean of Engr	Oregon State Univ
Frederick Merryfield	Prof of Sanitary Engineering	Oregon State Univ
Cameron M. Gilmour	Prof of Bacteriology	Oregon State Univ
Donald C. Phillips	Assoc Prof of Sanitary Engr	Oregon State Univ
Warren C. Westgarth	Assistant Professor	U.S. Public Health Service
Roscoe F. Ward	Research Assistant	Washington Univ
Robert I. Pailthorpe	Graduate Assistant	Consulting Engr
John K. Carswell	Graduate Assistant	U.S. Public Health Service
Lorus L. Purkerson	Graduate Assistant	Oregon State Univ
John Seaders	Graduate Assistant	Oregon State Univ
Lloyd Cox	Civil Engineering Student	Oregon State Univ
Michael D. Roach	Graduate Assistant	City of Portland, Ore
Sigurd P. Hansen	Graduate Assistant	Oregon State Univ

TABLE OF CONTENTS

Page

INTRODUCTION 1

CONCLUSIONS 3

- Removal of Beet Waste Color 3
- Persulfate Oxidizable Carbon 4
- Evaluation Criteria 5
- Kinetics of Biological Contact Beds 6
- Contact Time and Reaction Rates 7

APPENDIX

I. Kinetics of Biological Contact Beds

II. Contact Time and Reaction Rates of Trickling Filters

III. Reprints of Published Articles

- A. Evaluation Criteria for Deep Trickling Filters
- B. Persulfate Oxidizable Carbon and BOD as a Measure of Organic Pollution in Water

INTRODUCTION

Studies of the physical-chemical aspects of deep trickling filters have been conducted at Oregon State University to investigate their use in terms of the kinetics of the physical-chemical and biochemical reactions that contribute to filter efficiency or which retard filter operations. The study has also involved development of methods for measurement of filter efficiency. This work was initiated with the assistance of the Oregon State Sanitary Authority and other groups who felt that deep trickling filters might be useful in the treatment of certain food processing wastes in the Pacific Northwest, particularly those resulting from the processing of beets.

During the early work an experimental facility, consisting of a primary and secondary clarifier and a 20-foot deep trickling filter 4 feet in diameter with sampling ports at 2-foot intervals, was constructed adjacent to the Corvallis Sewage Treatment Plant. Filter media consisted of clean, rounded, river rock screened from 2.5 to 4 inches in diameter. (Reprint 65 - Appendix III) Facilities to load the filter with various rates of domestic and cannery wastes were included. Later, improvements provided for additional primary clarification and the addition of four separate filter units to provide flexibility in loading and study of comparative loading rates.

Phases of investigation recently completed utilized three filters of 5.8 inch diameter and 18-foot depth. Filter media consisted of 9/16, 7/8, and 1-1/4-inch spheres. Sampling ports in the filter towers allowed sampling of the water being filtered and examination of biological growth on the media. Studies included examination of removal rates of organic material as affected by media size, filter depth, and time of retention of liquid in the filter.

Research has been conducted by various student and staff investigators under the direction of Professor Fred Merryfield for the first 2-year period and Professor Fred J. Burgess during the last 3-year period. Findings of the various research approaches are tabulated in detail in the various sections of this report.

Experimentation during the period of study covered by this project has included the major aspects of:

a. Treatment of beet cannery wastes by deep filters;

b. Use of persulfate oxidizable carbon as a measure of organic pollution in water;

c. Criteria for evaluation of deep trickling filters;

d. Kinetics of deep biological contact beds;

e. Rate and mass transfer functions of biological treatment processes.

This report is organized in five major sections dealing with:

a. The objectives and conclusions obtained from each phase of study.

b. A description of facilities.

c. Suggested future research.

d. Research of graduate students that is, at this time, unpublished in professional journals.

e. Reprints of published works during the course of this research.

CONCLUSIONS

Objectives of research and resulting conclusions are listed below under the title of the project. They are arranged in order beginning with the initial study and progressing chronologically.

A. "Removal of Beet Color from Waste by Treatment with Trickling Filters," by Robert E. Pailthorp, refer to J.W.P.C.F. 34, 11, 1201 (November, 1960).

Objective:

To determine if conventional high-rate trickling filters would remove beet color when beet waste is treated in conjunction with domestic sewage.

Conclusions

1. Using high-rate trickling filters now found in municipal sewage treatment plants, there would not be adequate treatment to remove enough beet color (under conditions studied in Corvallis) from combined beet wastes and domestic sewage to prevent its detection in a receiving stream.

2. Increasing the circulation ratio increases the removal of beet color by trickling filters.

3. Decreasing the filter loading increases the removal of color and BOD.

4. It requires large amounts of chlorine to remove the color from beet waste, but the contact time could be short, and no sludge would be produced.

5. Lime treatment produces a good color reduction, but would require processing large volumes of sludge.

6. Other materials tested (ferric chloride, sodium chloride, activated carbon, carbon dioxide, ammonium hydroxide and sodium hydroxide) were not effective in removing color from beet wastes.

B. "Persulfate Oxidizable Carbon and BOD as a Measure of Organic Pollutants in Water," by John K. Carswell (Appendix III), Engineering Experiment Station Reprint Number 64.

Objectives:

1. The initial engineering application of the persulfate oxidation test for organic carbon in waste water.

2. Further investigation of the relationship between persulfate oxidizable carbon (POC) and biochemical oxygen demand (BOD).

Conclusions:

1. The term "persulfate oxidizable carbon" (POC) is preferable when referring to the results of the persulfate oxidation test applied to waste water analysis.

2. Sample pretreatment affects the magnitude of the values, but has little effect upon a BOD-POC relationship, providing similiar pretreatment is given to samples for either form of analysis.

3. In raw domestic sewage, carbon in forms other than true solution is measured by the persulfate oxidation test.

4. Direct measurement of the POC level in a standard BOD dilution is impossible due to sensitivity limits of the persulfate oxidation tests.

5. Limited general conclusions as to the rate of POC uptake during a standard BOD reaction may be made from the POC uptake during a Warburg BOD reaction because of similarity of oxidative mechanisms.

6. Graphs of Warburg and standard BOD versus POC utilized for raw

domestic sewage show a definite bias in favor of BOD.

7. BOD and POC utilized values for raw domestic sewage, show similar trends with time during the carbonaceous stage of the BOD reaction.

8. BOD and POC utilize values for raw domestic sewage become independent during the nitrification stage of the BOD reaction.

9. BOD data used to establish a valid relationship between BOD and the initial POC level of raw domestic sewage must be limited to values from the carbonaceous stage of the BOD reaction.

10. A valid comparison and POC removal efficiencies for the experimental trickling filter cannot be made because of the effects of nitrification.

11. In a pollutional situation where a valid BOD-POC relationship is known to exist, POC values alone may be used to evaluate the situation.

C. "Evaluation Criteria for Deep Trickling Filters," by F.J. Burgess (Appendix III), Engineering Experiment Station Reprint Number 65.

Objectives:

1. To determine operational characteristics of a deep trickling filter over the wide range of loadings reported in the literature (2)(3)(4)* on the relatively weak wastes typical of the area in order to determine the applicability of design standards for this case.

2. To evaluate the reliability of measurement indexes for testing treatment efficiency and loading, with particular emphasis on the relationship of water-soluable carbon and BOD.

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*Numbering of references coincides with references in report in Reprint Number 65 in the Appendix.

Conclusions:

1. Water-soluable carbon as measured by the persulfate oxidation test is a good measure of organic pollution in water and may be correlated to the 5-day BOD. The exact nature of the total relationship, however, is not completely understood and merits investigation.

2. Information gathered on 5-day BOD reduction and nitrification within the experimental filter substantiates Velz's observations (11) as expanded by Grantham et al. (2). Values of the reaction rate constant K in the expression

$$L_D/L = 10^{-KD}$$

are relatively lower at high organic and hydraulic loading rates involving weak sewage.

3. High hydraulic and organic loadings with the weak sewages examined yielded far lower than results predicted by theoretical formulas.

4. Oxidation rates with filter depth indicate that test facilities to be constructed with controlled media size and environment need not exceed 8 to 10 feet.

D. "Kinetics of Biological Contact Beds," by John Seaders (Appendix I).

Objective:

To investigate removal rates of organic substrates in sewage as affected by media size and filter depth.

Conclusions:

1. The 9/16-inch media is impractical as the clogging and ponding problem will cause system failure at any hydraulic rate. Only regular remedial action permitted continuation of testing.

2. The 7/8-inch and 1-1/4-inch marbles are both effective as media and more so as the hydraulic rates are increased. A maximum hydraulic rate using all available pore space as fluid passage would be a limiting factor in the rate of application.

3. The difference between the 7/8-inch and 1-1/4-inch media is negligable when the variation of the observations is subjected to analysis of variants and the 90 per cent significance level is used.

4. The limiting practical depth at rates below 30 mgad is about 8 feet.

5. High rates make greater use of the filter portion below 8 feet.

6. The K rates are considered as dependent upon hydraulic rates.

7. Total film quantities are of no influence in the degree of purification achieved. Some stratification with depth will occur depending upon where the greatest organic removal was effected; ie, there are no organisms where little is left to be removed.

8. The pH will drop with depth due to uptake of waste products. Release of gaseous waste products will cause pH to recover.

9. A negative or low ORP value is not necessarily indicative of a failing biological process, but in healthy cultures there presents a lag between activation of dissolved oxygen and oxidation of reduced metabolic waste products.

E. "Contact Time and Reaction Rates for Trickling Filters," by Michael Roach (Appendix II).

Objective:

To correlate the removal rates of organic material in the laboratory model of a trickling filter with the time of retention of liquid in the filter.

Conclusions:

1. Contact time for a liquid flowing through the filter bed without biota in the range of media size was found to be inversely proportional to the 0.76 power of the hydraulic loading, inversely proportional to the 0.50 power of the diameter of the media, and directly proportional to the 1.08 power of the filter depth.

2. Contact time for a liquid flowing through the filter bed with biota in the range of media size was found to be inversely proportional to the 1.05 power of the hydraulic loading and directly proportional to the 1.44 power of the filter depth.

3. Contact time is not influenced by media size for filter media covered with biota.

4. Flow rate has a greater influence on contact time for media with biota than for the media without biota.

5. Depth has more influence on contact time than any other variable for media both with and without biota.

6. Depth has a greater effect on contact time for the media with biota than the media without biota.

7. The fraction of COD remaining is inversely proportional to the 0.19 power of the contact time.

KINETICS OF BIOLOGICAL CONTACT BEDS

by

JOHN SEADERS

A THESIS

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in partial fulfillment of
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degree of

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APPROVED:

____

Assistant Professor of Civil Engineering

In Charge of Major

____

Head of Department of Civil Engineering

____

Chairman of School Graduate Committee

____

Dean of Graduate School

Date thesis is presented: __________________________

Typed by Mary Coslet

TABLE OF CONTENTS

INTRODUCTION 1

- Purpose 2
- Scope 2

REVIEW OF LITERATURE 3

- Media Type and Size 3
- Depth and Loadings 5
- Film and Contact Time 6
- Ventilation 7
- pH 8
- ORP 9
- Temperature 10

EQUIPMENT AND METHODS 10

- Equipment 10
- Substrate Analysis 16
- Methods 17
  - Data Collection and Sample Preparation 18
  - Preliminary Testing 19
  - Method of Data Analysis 21
  - Filter Operation Diary 25

DISCUSSION OF DATA 26

- Media Size Influence upon Effluent Quality (COD) . . 26
- Media Size Influence upon Effluent Quality (BOD) . . 29
- Biological Growth 30
- pH 40
- ORP 44
- Temperature 48

SUMMARY 48

CONCLUSIONS 52

SUGGESTIONS FOR FUTURE RESEARCH 53

BIBLIOGRAPHY 55

APPENDICES 58

LIST OF FIGURES

Fig. 1. Schematic Flow Diagram -- Experimental Filter Unit 14

2. Experimental Filter Units 15

3. Sampling Port in Column III with Tray 15

4. Percent Acid in Digestion Mixture 22

5. BOD vs. Time, Influent and Effluent, Columns II and III @ 60 mgad 23

6. BOD vs. Time, Influent and Effluent, Columns II and III @ 75 mgad 24

7. Percent COD Remaining vs. Depth, Column I, Data Test Run 1 - 3 31

8. Percent COD Remaining vs. Depth, Column II, Data Test Run 1 - 5 32

9. Percent COD Remaining vs. Depth, Column III, Data Test Run 1 - 5 33

10. Percent COD Remaining vs. Depth, Data Test Run 1, Columns I, II and III 34

11. Percent COD Remaining vs. Depth, Data Test Run 2, Columns I, II and III 35

12. Percent COD Remaining vs. Depth, Data Test Run 3, Columns I, II and III 36

13. Percent COD Remaining vs. Depth, Data Test Run 4, Columns II and III 37

14. Percent COD Remaining vs. Depth, Data Test Run 5, Columns II and III 38

15. gm's/Unit Surface Area vs. Depth, Column I, Data Test Run 2 and 3 41

16. gm's/Unit Surface Area vs. Depth, Column II, Data Test Run 2 - 5 42

17. gm's/Unit Surface Area vs. Depth, Column III, Data Test Run 2 - 5 43

18. pH vs. Depth, Typical Curves 45

19. ORP vs. Depth, Typical Curves 49

APPENDIX

A. Analysis of Variance 59

B. Summary of Experimental Data 68

C. Stockfeed and Hydraulic Loading Rates As Percent of Intended Rates 88

LIST OF TABLES

Equipment and Methods

Table 1. Marble Size Analysis 11
2. Marble Weight Analysis 11
3. Substrate Analysis 17
4. Acid Percentage 20
5. Digestion Time 21

AN ABSTRACT OF THE THESIS OF

John Seaders for the Master of Science in Civil Engineering
(Name) (Degree) (Major)

Date thesis is presented ____________________.

Title The Kinetics of Biological Contact Beds

Abstract approved ______________________________
(Major Professor)

The influence of media size upon the effective removal of organic waste from a liquid substrate was studied by the use of three experimental trickling filters under a set of uniform operating conditions. The range of experiments involved hydraulic loadings of increasing magnitude and of constant organic strength.

The trickling filter columns consisted of three 18-foot, 5.8-inch diameter pipes with ports cut at various levels to permit the taking of samples and observation of conditions existing within the media mass.

The media selected for the analysis were 9/16-, 7/8- and 1-1/4-inch diameter marbles which were placed in the columns in such numbers that the surface areas were related in the ratio of the inverse diameter of the marbles.

The data collected for a basis of analysis were COD, BOD, film quantity, pH, ORP and temperature at influent, 1-, 2-, 4-, 8-, 12- and 18-foot or effluent levels. The other variable introduced intentionally was the hydraulic loading rate which started at 15 mgad and was increased to 75 mgad in 15 mgad steps between data test runs. A data test run consisted of five consecutive tests at each sampling point for each of the items selected as data basis.

The performance of the three filter columns was measured in terms of BOD and COD removals. These performance data were subjected to an analysis of variance to detect significant differences between columns. There were observable differences in Columns II and III, but at the 90 percent significance level the analysis of variance showed a similarity in treatment capacity at each level and each rate applied between these filter units.

Failure to pass hydraulic loads above 45 mgad put Column I out of the test series. This left Columns II and III for comparison at the 60 and 75 mgad rates.

The performance of the filter columns showed that the 9/16-inch marbles were not a practical size media for use in a trickling filter, as clogging and ponding made the filter very hard to maintain and operate. COD and BOD removals became less and less, and the filter failed to function satisfactorily above the 45 mgad rate.

The 7/8- and 1-1/4-inch media both maintained treatment capacity at the maximum rates applied. The measurable conditions indicated a much greater removal of organic load in total organic material removed at the higher rates than at the lower rates even though effluent quality deteriorated. The high rates of application favor the creation of a healthy environment for bacterial growth in providing better ORP and pH conditions.

The media size and thus surface area is shown to be of great influence in the establishing of optimum treatment conditions. The media size should be small enough to provide for a large amount of surface area per unit volume of media yet large enough to provide for a pore space giving adequate reaeration and fluid passing channels.

The smallest media tested does not meet these requirements, while the larger size media tested appeared to meet them better at the higher rates of application.

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John Seaders

INTRODUCTION

In the biological treatment of settled domestic sewage by trickling the sewage over a bed of inert media, there are many factors which affect the removal rate of the organic material by the biological contact bed. The major physical factors which are subject to control are: temperature, size and shape of filter media, depth of filter, the organic and hydraulic loading rates, and the air circulation through the filter. For any one combination of these factors there is a rate at which the organic materials are removed from the sewage by the biota in the bed. Each factor has limits beyond which it exerts such influence upon the system that the efficiency of the bed is destroyed.

The media size may be considered to vary from sand to huge rocks. Common sense would suggest a media size somewhere between such extremes. Experience with trickling filters has somwhat limited the range of sizes and the materials used for this purpose. The purpose of the media is to provide a surface upon which the micro-organisms can grow. The lower limit for media size, however,is determined by requirements for flow (food supply and cleaning action) and ventilation and with some types of industrial wastes by the type of organisms in the bed. The limiting depth of a filter would be the depth where the rate of removal is such that it is no longer removing the organic materials from the substrate efficiently in terms of the cost involved in constructing the filter bed.

In doing this work, it is hoped that a conclusion may be made which will enable the prediction of filter performance by analysis of the physical properties of the bed and the organic and hydraulic loads imposed on it.

Purpose and Scope

The purpose of this thesis is to investigate removal rates of organic substrates in sewage as affected by media size and filter depth.

The scope of this work is limited to five data runs. Each run consists of a series of five sets of tests. A single set of tests encompasses the taking of samples from each filter column at the influent, 1-, 2-, 4-, 8-, 12-foot and effluent levels and the analysis of these samples for temperature, pH, oxidation-reduction potential, chemical oxygen demand and five-day, 20° C., biochemical oxygen demand. At the end of a test run bacterial growth samples were taken at each of the sampling levels for determination of weight of growth per unit of surface area. During a five-day test series BOD_5 were obtained for three of the five days.

REVIEW OF LITERATURE

Introduction

A review of the literature shows that trickling filters have had extensive use in the secondary treatment of sewage and industrial wastes. The literature contains numerous articles which report operational data and experimental investigations on high-rate and low-rate trickling filters; however, few articles have referred to the influence of media size per se upon the performance of trickling filters.

The literature review which follows was prepared in recognition of the accumulated knowledge and experience of previous investigators. In addition to a section devoted specifically to media type and size, other sections have been provided to indicate the significance of several factors which were considered to be pertinent to this thesis.

Media Type and Size

For the support of the biological mass an inert media is required. A wide assortment of materials has been used and some differences, however minor, have been found to exist between different types. The selection of materials ranges from slag, coke and limestone to wooden slats and prefabricated plastic cells. Location of available materials influences the choice of media in most instances and the process requirements in others. Most commonly, a well-rounded river gravel or crushed stone is used. The general viewpoint about filter media material is that any uniform, inert, hard material is suitable as filter media.

In a thesis presented to Purdue University, J. C. McDermott proposed a design equation for surface area requirements based on a desired degree of purification, in terms of COD and applied hydraulic loads.

The size of the media is as yet an empirical selection; but since it is felt that the best purification is obtained by adequate contact time and that contact time per unit of filter is greatest for the smallest media used, it is best to use the smallest media practical. Investigations with 3/4-inch media at standard rates showed serious problems with clogging even though a positive pressure head was maintained with forced air. Experiments with 3/4-inch Raschig rings, when compared to other types and sizes of materials, gave the best results. Designers favor the use of filter media ranging from two to four inches in size, but the indications are that the smallest practical size is to be preferred to obtain a given contact time at maximum efficiency. However, the literature does not indicate the smallest practical size and the operating conditions which should be used for successful operation. (2, 5, 8, 11, 15, 16, 17)

Depth and Loadings

Filter depth has received prime attention by investigators due to the fact that direct financial benefits were to be gained from the results. Earliest filters were designed empirically. With testing and data becoming available, attempts have been made to obtain some design formulations for depth requirements in terms of loadings and efficiency desired. The thinking with respect to loadings has changed drastically with time. The early experiments at Lawrence Experiment Station in England in 1889 limited hydraulic rates to about two mgad for optimum results. Present testing at high rates indicates that good treatment can be obtained at loadings once considered out of question.

In general, it has been found that increasing BOD and hydraulic loadings results in poorer effluent, but the total removal in number of pounds of BOD or COD is greatly increased. Research, when related to depth, shows that the greater amount of BOD is removed in the upper part of the filters, and the removal rates have been demonstrated to follow a straight-line semilog function when the removal is figured as percent removal of the total amount of removable organic material entering a section of filter.

A limiting depth of eight feet is considered the economic limit for trickling filters how being designed since the extra efficiency obtained does not, in most cases, warrant the added cost of filter construction. When the rate of application is increased and BOD strength maintained constant, the effect on effluent strength has been reported nil up to loadings of 30 mgad. (1, 2, 4, 5, 9, 25)

Film and Contact Time

Differences in film quantity between high-rate and standard filters have been attributed by investigators to incomplete absorption and removal of the load by the high-rate filter because of inadequate contact time. Contact time is the increment of time during which a given part of a bacterial population has the opportunity to remove organic materials from the substrate. Predictable variations in film quantity have been noted with variations in applied BOD load and seasonal temperature variations.

At one time film quantity was considered to be directly proportional to the purification achieved, and design formulas for trickling filters based on film quantity per unit of filter media have been proposed but have not found general acceptance.

The latest indications are that the mass of slime or biota has little or no relationship to contact time or degree of purification. This thought is based upon the consideration that the active area of the slime layer is the outermost layer and that underlying layers are not as active as once was thought. Also, the underlying layers are thought of as a reservoir for fluid storage and not as contributing to increasing the contact time.

Initial experiments with trickling filters showed that for highest efficiency in terms of percent BOD removed, a very thin film of fluid moving very slowly over a film of organisms was the ideal criteria for contact time. BOD is usually defined as the oxygen required by organisms to stabilize organic materials under aerobic conditions. Recently, contact time T has been related to filter depth D and hydraulic loading Q; the contact time was found to vary directly with filter depth and inversely with hydraulic loading according to the equation:

$$T = 30.2\ D^{1.08}\ Q^{-0.515}$$

(1, 2, 3, 7, 9, 10, 23, 25)

Ventilation

There is still a great deal of controversy about ventilation. Investigations on bottom ventilation, side ventilation, forced and top ventilation are reported and the merits of each scheme have their adherents. The mass of evidence as shown by the more closely controlled experiments indicate, however, that adequate ventilation aids substantially in the waste stabilization process. The purpose of ventilation is still controversial; some feel it aids directly in the metabolic processes and in maintaining a positive oxidation-reduction potential, which is the ratio between materials in the reduced form and materials in the oxidized form, conducive to more rapid oxidation of soluble and colloidal waste products, while others think that the main purpose is to remove gaseous waste products. (5, 6, 7, 13, 14, 19)

pH

The pH sensitivity of biological treatment processes has almost been an accepted axiom for years. Experiments with domestic wastes and adjusted pH's have indicated that although the pH affects the treatment plant efficiency, the biological treatment process is not so sensitive that the system is upset to the point of failure. Good treatment efficiency has been obtained with pH between 8 and 9, but at pH 11 the results became poor. However, the filter was able to reduce the pH from 11 to 9. Low pH ranges soon become toxic and can destroy the process. For specific wastes it has been demonstrated that a pH range of 5 to 8 has only a slight effect on the effluent quantity. (21, 27)

ORP

The influence of the oxidation-reduction potential has been under study for some time, and ORP is presently considered to be dependent on two different reactions. One reaction, which is enzymatic, changes the dissolved oxygen into activated oxygen which is then able to take part in biochemical reactions. The second reaction is between this activated oxygen and the reduced waste products from the metabolic processes. In vigorous cultures the second process takes place faster than the first, and the activation rate becomes the limiting process. Particular enzyme systems, as well as the diffusion rate of oxygen from free oxygen to dissolved oxygen and the transfer of dissolved oxygen to the active reactions area, will influence the activation rate. The thinking has been that a high dissolved oxygen content indicated a good ORP; but when the activation process is proceeding rapidly, the stabilization process of reduced products will proceed as fast or faster. This suggests that even though the dissolved oxygen is low because of rapid activation, the process may be in excellent condition in terms of reduced waste products being stabilized. On the other hand, if the activation rate is lagging, the reduced products may increase, causing a sharp drop in ORP even though an excess of dissolved oxygen exists. If there is no source of oxygen available, the medium becomes conducive to the action of anaerobic enzymes which take over, and the ORP remains low. (24)

Temperature

The literature is in agreement that within the limits of the temperature growth range for organisms, it is important to create temperature conditions which fulfill the requirements for optimum growth conditions for a maximum number of organisms. At such temperatures the metabolic activity is nearer optimum for most organisms, and thus cell division takes place at a higher rate, producing a larger cell mass engaged in stabilization of organic materials.

Several reports indicate an increase of 25 percent in BOD removal between summer and winter. However, at depths greater than six feet no difference could be shown. The high-rate filters which have come into use are even less influenced by seasonal variations, as the great influx of liquid mass and the latent heat of this mass prevent the filter mass from cooling to lower efficiency levels. (20, 21, 22)

EQUIPMENT AND METHODS

Equipment

Three trickling filters of 5.8-inch diameter and 18-foot depth were constructed for testing under controlled conditions. Each column was packed with a media of constant size; the size and type media selected for this study were 9/16-inch and 7/8-inch marbles and 1-1/4-inch ceramic spheres.

An analysis of 25 marbles of each size was performed to determine the mean diameter per sphere. The diameter of the spheres was taken in three cartesian coordinate directions. A summary of this analysis is shown in Table 1.

Nominal size in inches	9/16	7/8	1-1/4
Mean diameter in mm. of 25 marbles	14.14	23.28	31.43

In order to load the columns uniformly in each section of column, the weight of five samples of 100 marbles each for the smaller-sized media and five samples of 50 marbles each for the largest media was determined. This permitted loading by weight rather than counting out each marble. The results are given in Table 2.

Size of media	9/16	7/8	1-1/4
Mean wt./marble, gms.	3.57	16.24	38.25

In order to obtain a degree of uniformity between columns, the surface area provided per filter column was based on the ratio of inverse diameters of the media sizes used.

Ratio Calculation:

Diameter	9/16	7/8	1-1/4
Diameter	D_1	D_2	D_3
Area/unit of media	A_1	$A_1\left(\frac{D_2}{D_1}\right)^2$	$A_1\left(\frac{D_3}{D_1}\right)^2$
Volume/unit of media 4/3 D^3	V_1 total	V_2 total	V_3 total
Number of marbles/section	N	$N\left(\frac{D_1}{D_2}\right)^3$	$N\left(\frac{D_1}{D_3}\right)^3$

From the above tabulation, the following may be set up:

$$A_1 \text{ total} = N\ A_1\left(\frac{D_1}{D_1}\right)$$

$$A_2 \text{ total} = N\left(\frac{D_1}{D_2}\right)^3 \times A_1\left(\frac{D_2}{D_1}\right)^2 = N\ A_1\left(\frac{D_1}{D_2}\right)$$

$$A_3 \text{ total} = N\left(\frac{D_1}{D_3}\right)^3 \times A_1\left(\frac{D_3}{D_1}\right)^2 = N\ A_1\left(\frac{D_1}{D_3}\right)$$

$$\frac{A_{1T}}{D_1} = \frac{A_{2T}}{D_2} = \frac{A_{3T}}{D_3}$$

Then using D_2 as unity, the ratio between surface areas based on the ratio of the inverse diameters becomes:

$$\frac{1}{D_1} : \frac{1}{D_2} : \frac{1}{D_3}$$

$$\frac{1}{\frac{14.14}{23.28}} : \frac{23.28}{23.28} : \frac{1}{\frac{31.43}{23.28}}$$

$$1.645 : 1 : 0.741$$

In both the one- and two-foot sections this ratio of surface areas was maintained.

In the top five feet of the columns, sampling ports were constructed at one-foot intervals and in the remaining part of the column at two-foot intervals. Sampling trays were placed in the ports to aid in the removal of growth samples at various levels (Plate 1). Wall effects were minimized by drip rings at each sampling port to redistribute the flow clinging to the walls. The influent feeding apparatus was constructed so that constant feeding and feed strength could be maintained.

The original setup used three sets of two tanks of 100 L. each, each filter having its own feeding apparatus (Plate 2). The schematic diagram (Fig. 1) shows the flow pattern of the feeding arrangement.

The stockfeed tank contained the concentrated feed which was fed into a feed-mixing tank by a pneumatically operated positive displacement pump. A solenoid valve operated by a timer determined the frequency and rate of stockfeed supply to the mixing tank.

The feed-mixing tank contents were kept at a constant level by a float valve. The constant rates of incoming liquids and outgoing products insured a constant strength feed. Recirculation pumps provided mixing of influents and supplied the feed to rotary distributors.

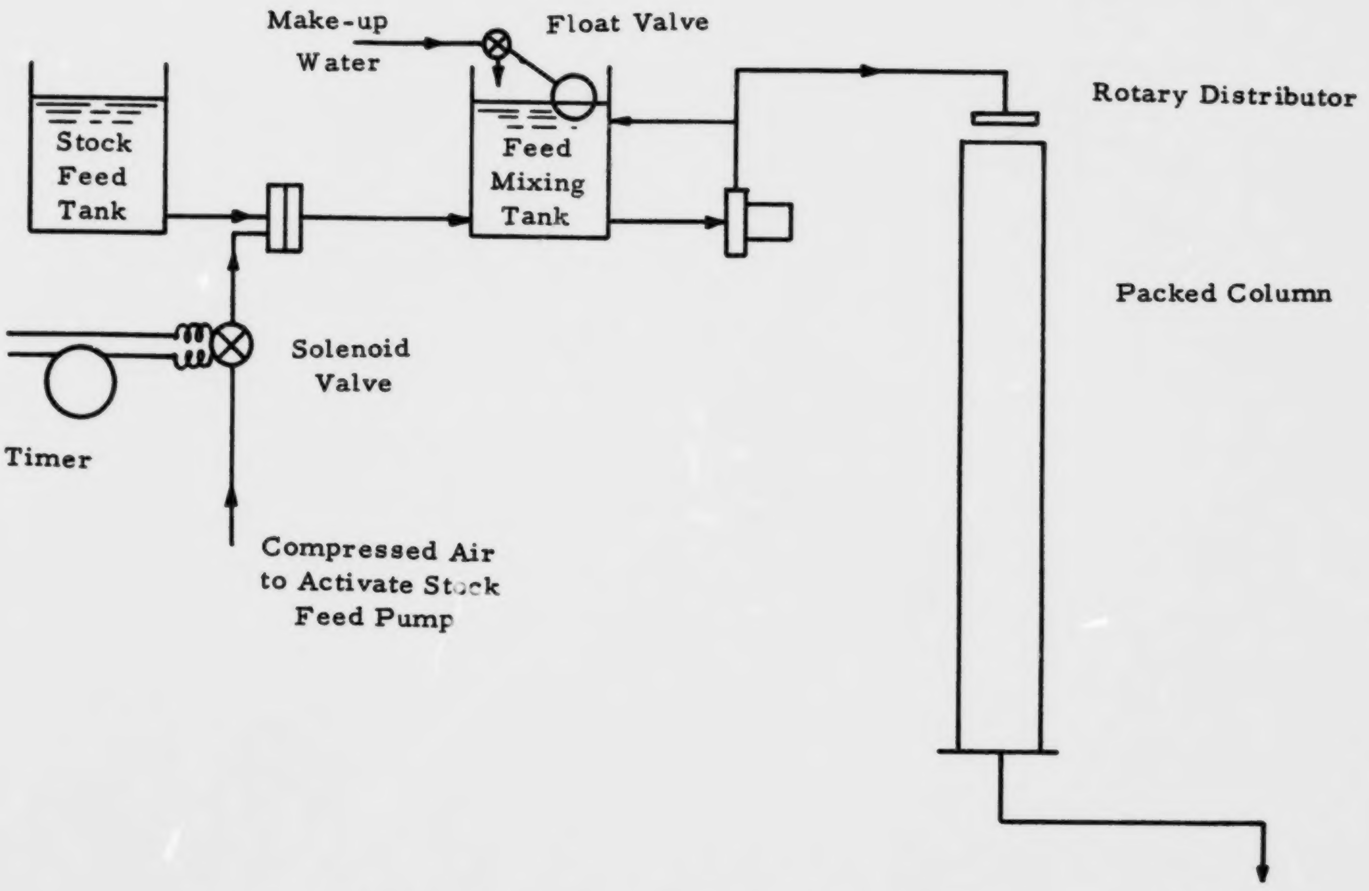

Make-up
Water
Float Valve
Stock
Feed
Tank
Feed
Mixing
Tank
Rotary Distributor
Packed Column
Solenoid
Valve
Timer
Compressed Air
to Activate Stock
Feed Pump
To Drain

Fig. 1. Flow Diagram -- Experimental Filter Units

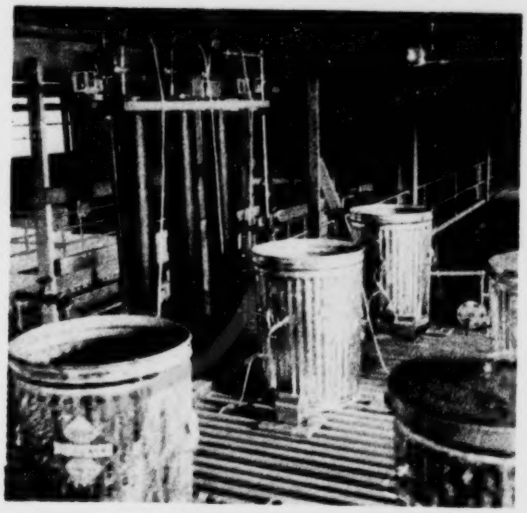


Fig. 2. Loading and Control Platform -- Laboratory Units

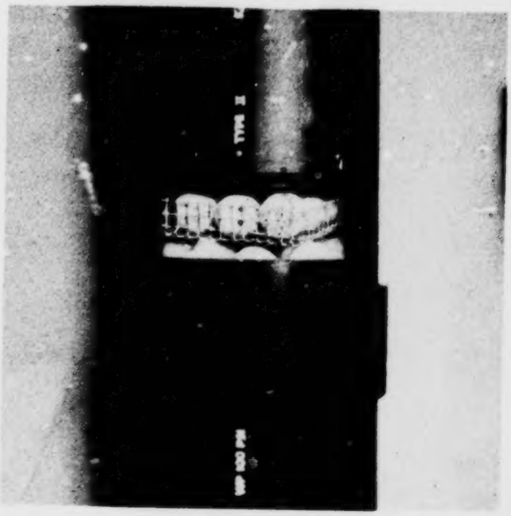


Fig. 3. Typical Sample Ports -- Laboratory Filter Units

The hydraulic rates to the filters were controlled by stop-cock valves. All lines to the feeding mechanisms were cleaned daily and the stop-cock valves adjusted to give the desired rate. The rates were measured before and after cleaning. The average daily rates are recorded in Appendix C.

The design of the filter units allowed for loadings from low rates to rates up to 120 mgad. For a change of loadings from 15 mgad to 30 mgad the rates were stepped up in five increments of three mgad at two-day intervals while maintaining a constant feed strength.

This system was modified in its operational procedure when bacteria growths in the feed lines interrupted continuous flow rates and at time stopped flow altogether.

A rotation procedure was adopted using one set of tanks per day for feeding while the other two sets were cleaned by continuous washing with a diluted "Purex" solution and rinsed with tap water. This system insured cleanliness at every point in the feeding system. During the hot summer days, the stockfeed tanks had to be abandoned as the milk used for substrate stockfeed went sour and curdled. Refrigeration of the stockfeed solved this problem satisfactorily.

Substrate Analysis

The milk solids used for organic load to the filter columns were analyzed for the following:

COD
BOD
Nitrogen as ammonia
  organic nitrogen
  nitrites
  nitrates
Phosphorus as PO_4

For methods of analysis the procedures outlined in the eleventh edition, 1960, of Standard Methods for the Examination of Water and Waste Water published jointly by the APHA, AWWA and WPCF were used. A Bausch and Lomb spectrophotometer was used to analyze the samples. Standard curves for NH_3, NO_3 and PO_4 were prepared.

The results of the analysis, tabulated in Table 3, are recorded as mg. per gm. of dry milk solids.

COD		1075	mg./gm.
BOD		700 - 775	"
Nitrogen:	Organic -- N	50	"
	Ammonia -- NH_3	0	"
	Nitrite -- NO_2	0	"
	Nitrate -- NO_3	0	"
Phosphorus:	Phosphate -- PO_4	29	"

Methods

The intended organic load was approximately 120 to 140 ppm of five-day BOD. Preliminary testing with milk solids showed that a BOD strength of 130 to 140 ppm and a COD strength of 220 ppm would be supplied by 0.2 gm. of milk solids per liter of water. The chemical oxygen demand is the amount of oxygen required by the organic materials if they were participating in a chemical reaction. The 0.2 gm. per liter was used as the standard feed for all operations, and the feed strength was maintained for the major part of the time within ten percent of the desired concentration (Fig. 18).

Data Collection and Sample Preparation

To establish the influence of media size, the substrate quality at various levels was required. Samples were taken at the 0-, 1-, 2-, 4-, 8-, 12- and effluent or 18-foot levels, and analyzed for ORP, pH, temperature, COD and BOD. The ORP, pH and temperature data are tabulated in Appendix B.

The samples were collected by means of channeled trays inserted in the sampling ports and then funneled into BOD bottles. The preparation of all samples from time of sampling until testing was accomplished in two to four hours.

Each sample was filtered through No. 40 Whatman paper to render the effluent comparable to settled trickling filter effluent. For BOD testing no seeding was needed except for the influent.

To obtain growth samples, marbles were lifted out of the trays (Fig. 2) with all growth that adhered or seemed to belong as having grown on that specific marble.

Forty, fifteen, and eight marbles were taken from Columns I, II and III, respectively, at each sampling level except the top. This number of marbles per column represented a unit of surface area approximately 250 cm^2. The marbles were then washed in distilled water and the thus-obtained growth dried in an oven at 103° C.

Preliminary Testing

Because of the weak nature of the waste, the standard COD test method had to be modified in order to employ it as a test for sample analysis.

The dichromate strength was reduced from 0.25 N to 0.10 N. This introduced a constant error of about 5 to 10 percent. Next, the sample size was increased from 50 ml. to 150 ml. This permitted digestion and titration of all samples with the same dichromate and titrant normality. The variation in results due to the different acid percentage was obtained by running a series of tests with samples of 25 ml. diluted to 25, 50, 75, 100 and 150 ml. with varying acid volumes of 25, 50 and 75 ml. per sample. The results of this test are tabulated in Table 4 and are shown in Fig. 4. The difference between the standard method and the modified method was computed to be 1.55. This, then, means that all COD values obtained were to be multiplied by a factor of 1.55, for each COD sample was brought to the same acid percentage by dilution.

Since the number of tests required was large, the possibility of reducing the digestion time was investigated. Samples of like strength and dilution were digested for one-half, one, one-and-a-half and two hours (Table 5). No difference was observed and, therefore, the digestion time of 45 to 60 minutes was employed throughout the testing period.

To ascertain the way in which the BOD samples used available oxygen, two sets of ten-day BOD samples were taken. The main purpose was to ascertain if the nitrification stage had been reached within the five-day period in which the samples taken during the data runs were reported.

The curves taken from this data are shown in Figs. 5 and 6.

Table 4.

Sample Volume	Acid Volume					
	25		50		75	
	% Acid	COD	% Acid	COD	% Acid	COD
25	33.3	157	50.0	221	60.0	254
50	25.0	141	40.0	176	50.0	216
75	20.0	129	33.3	151	43.0	189
100	16.7	126	28.6	141	37.5	160
150	12.5	112	22.2	129	30.0	141

$K_2Cr_2O_7$ Normality -- 0.1

$Fe(SO_4)NH_3$ Normality -- 0.1

Table 5.

Sample Number	Digestion Time Hrs.	Titrant Volume ml.
1	0.5	20.25
2	1.0	20.10
3	1.0	20.10
4	1.5	20.20
5	1.5	20.00
6	2.0	20.20

Method of Data Analysis

To establish significant differences between the media sizes used, the data was subjected to a one-way analysis of variance. In order to use the analysis of variance, all COD data was reduced to percent COD remaining at each level used for testing. Plots of these data are shown in Figs. 7 to 14, where each point represents the average of five tests or ten in some cases.

The hypothesis was that there was no significant difference at the 90 percent significance level. Fisher's F value was used to determine whether the hypothesis was true or false. Then, to compare the filter columns further, the single degree of freedom was used to check for differences between two columns. The results of the analysis of variance are tabulated in Appendix A.

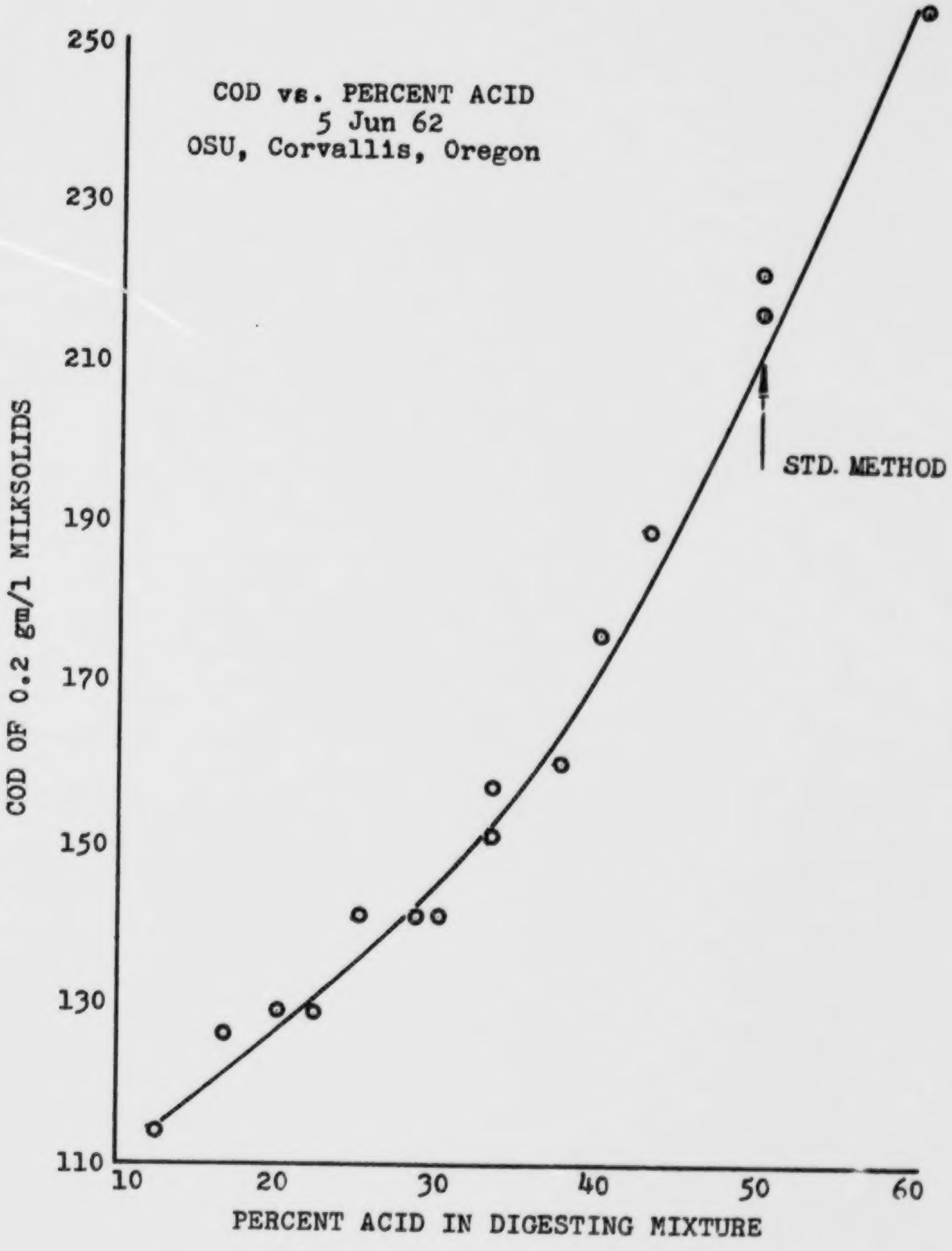

COD vs. PERCENT ACID
5 Jun 62
OSU, Corvallis, Oregon
250
230
210
190
170
150
130
110
COD OF 0.2 gm/1 MILKSOLIDS
STD. METHOD
10
20
30
40
50
60
PERCENT ACID IN DIGESTING MIXTURE

FIG. 4

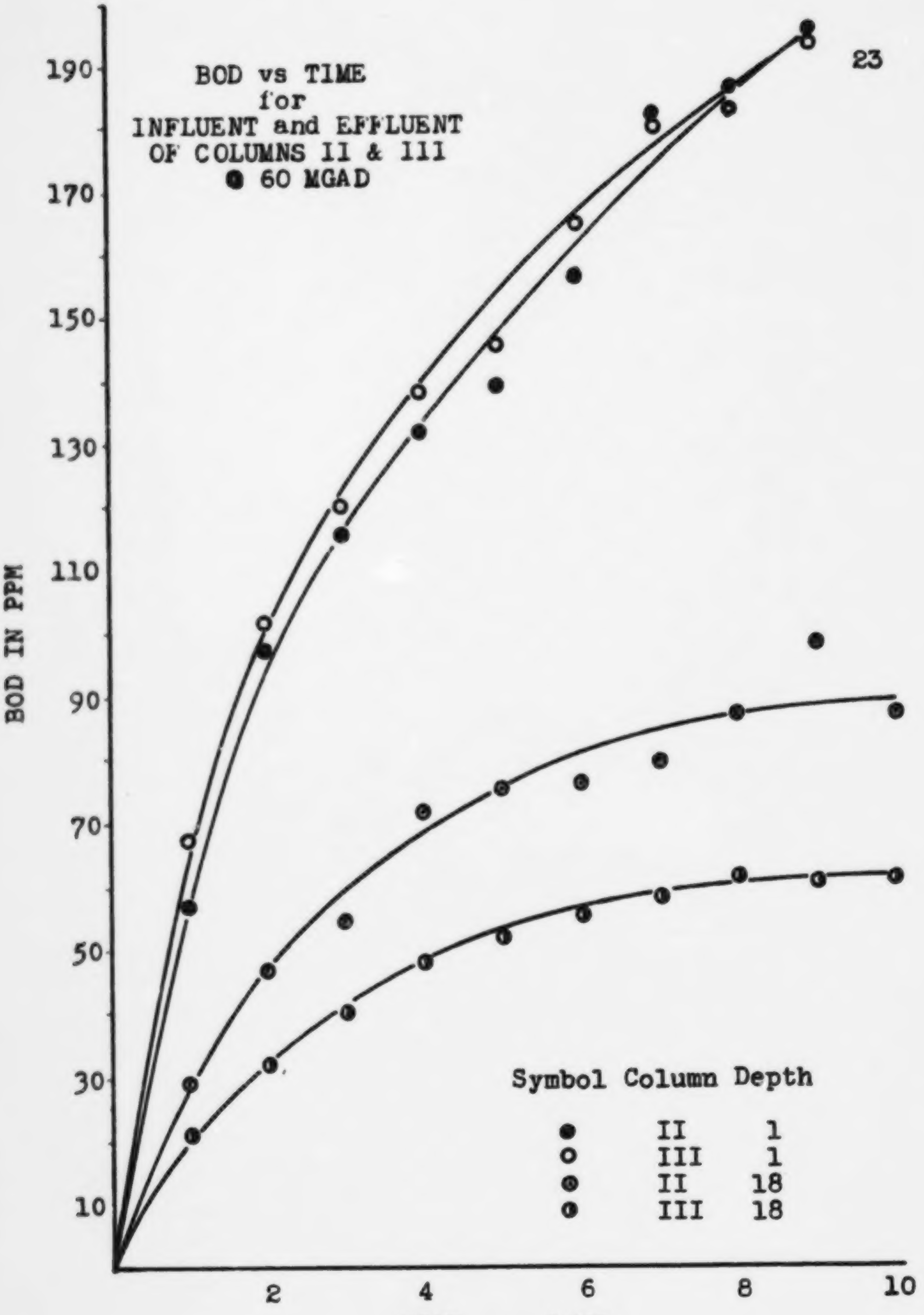
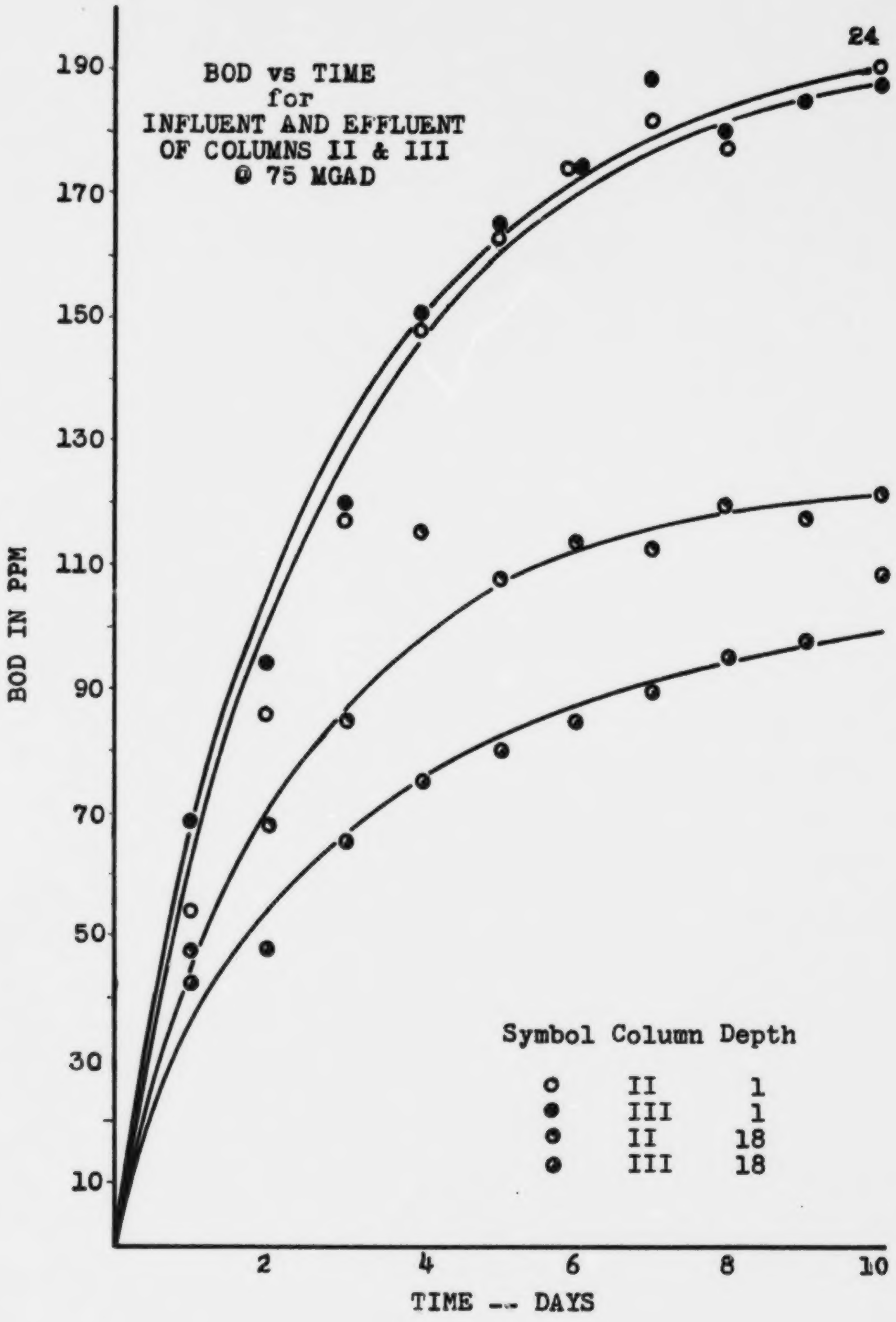

BOD vs TIME
for
INFLUENT and EFFLUENT
OF COLUMNS II & III
@ 60 MGAD
23
190
170
150
130
110
90
70
50
30
10
BOD IN PPM
2
4
6
8
10
TIME --- DAYS
Symbol Column Depth
● II 1
○ III 1
◉ II 18
◉ III 18

FIG. 5



BOD vs TIME
for
INFLUENT AND EFFLUENT
OF COLUMNS II & III
@ 75 MGAD
24
BOD IN PPM
190
170
150
130
110
90
70
50
30
10
2
4
6
8
10
TIME -- DAYS
Symbol Column Depth
○ II 1
● III 1
⊙ II 18
⊙ III 18

FIG. 6

Filter Operation Diary

Filter operation started April, 1962, with seeding of settled domestic sewage and the introduction of artificial substrate. The initial rate was set at 15 mgad and a growing period of six weeks was considered adequate for the establishment of equilibrium conditions.

During this period only slight bacterial growth was observed below the eight-foot level in the filter with the smallest media, hereafter to be referred to as Column I, or below the six-foot levels in the filters with 7/8-inch and 1-1/4-inch media, to be referred to as Columns II and III, respectively.

From the bottom of the screens which supported the media in each section, growth occurred repeatedly (after cleaning) in the shape of icicles and of rubbery texture. The icicle shapes developed, no doubt, due to channeling effects within the filter mass. This excess growth was removed at regular intervals. The loss of active organisms can be considered nil, for only the outer layers were in contact with passing liquids.

Ponding and the associated anaerobic conditions were first noted in Column I and to some degree also in Column II at the initial rate. At higher rates, however, when remedial action was applied by draining the section and agitation of the media, aerobic conditions were brought about and persisted. Due to the small diameter of the columns (5.8 inches), wall effects were anticipated to be a problem. The problem was overcome by drip rings which tended to redistribute this flow over the center portion of the column section. Observations showed that the dispersion of liquid through the media after the liquid passed through one foot of filter was no problem.

Filter fly problems were not encountered to any great degree. Filter flies began to show up at the end of June, but as the rates were increased, the flies decreased.

DISCUSSION OF DATA

Media Size Influence upon Effluent Quality (COD)

Figs. 7, 8 and 9 are plots of the percent COD remaining vs. depth for each filter column. The flattening out of the curves indicates that greater use was made of the lower part of the column as the hydraulic rates went up. Even though in Fig. 8 the COD of the effluent increased from 10 percent remaining to 33 percent remaining, the total pounds of COD removed was almost four times greater at 75 mgad than at 15 mgad.

Increase of COD in the effluent but greater removal of applied weight of organic material can also be seen for Column III, while Column I shows this trend only for the upper 12 feet of the column. Almost every curve plotted showed a flat slope at the top of the column. This is probably due to a gradual change-over from aerobic to anaerobic conditions during initial rates of application. Some degree of clogging and insufficient sloughing were noticed in every column. The clogging problem decreased from Column I to Column II. But once the anaerobic condition prevails, it is difficult to reverse the process until aerobic conditions prevail. The anaerobic section also progressed to some extent downwards with increasing rates. See Figs. 7 and 8 for Columns I and II. But after the rates went up to where flushing became substantial, a reversal was indicated.

The analysis of variance of the COD data collected from five data test runs (Appendix A) gave the following indications on the influence of media size upon the effluent quality. At the initial rate of 15 mgad the media size showed a significant influence upon the purification results at almost every level in the columns. At the increased rates this influence diminished, and only the bottom sections of the filters showed significant differences. The choice of which media size is to be preferred at what rate is only arrived at by a comparison between the columns in pairs.

The Analysis of Variance calculations as well as visual inspection of the COD and BOD remaining vs Depth curves, indicate with the exception of Run 1, that Columns I, II and III have the same purification capacity at every hydraulic loading imposed on the systems. If Column 1 had not clogged over most of its length this trend might have been established more firmly. Comparisons between individual columns lead to the same conclusions. The real difference between columns is not their ability to purify the wastes but to remain in operation without the need of remedial action. The analysis of variance, exclusive of data run 1, showed that 90 percent of the F values obtained from the comparison of Columns II and III are below the F value at the 5 percent significance level. This established the hypothesis that Columns II and III are alike and, therefore, that the difference between 7/8-inch and 1-1/4-inch media is of no consequence in the purification of waste when the results are reported in terms of COD.

The smallest (9/16-inch) media began to exert detrimental influence upon the facility soon after operations started. After repeated efforts to keep the system operational at 60 mgad failed, the column was taken out of action. The requirements for growth, aeration and fluid passage could not be met by the smallest media when the rates were increased above 45 mgad. The closure of available channels for fluid flow by growth in the voids most certainly attributed to the failure of the system. The closure of channels did not proceed as rapidly or did not occur at all with the larger media sizes in Columns II and III.

Media Size Influence upon Effluent Quality (BOD)

An analysis of variance was also made of the BOD data at the 4, 8, 12 and effluent levels. The F values obtained from this analysis are shown in Appendix A.

The results of this analysis agree with the COD data analysis in that Columns II and III are shown to have the same degree of variation and are the same in purification capacity at the 5 percent significance level.

As in the COD analysis the columns are quite similar in results produced by the upper section of filter column during the first three data runs. But the lower sections showed marked differences beginning at the 12- and 8-foot depth at 30 and 45 mgad loadings, respectively.

The effluent of Column I in terms of BOD deteriorated rapidly at the higher rates due to poor contact conditions resulting from clogging and ponding.

There is a similar increase in total removal and greater activity in the lower part of the filter columns evident in BOD results as was shown by the COD results. This would indicate that the percent removal of BOD and COD as a percent of removable fraction present at entering a section was decreasing at the higher rates.

This removal rate or K rate is defined as the rate of extraction or organic material per interval of depth of a biological contact bed, and this rate is proportional to the remaining concentration of organic matter measured in terms of its removability.

Therefore, the K rates may vary with hydraulic loads.

Biological Growth

The growth patterns as determined by the dry weight of biological mass are shown in Figs. 15, 16 and 17. Despite the scattered pattern, some observations and conclusions may be made.

First, the variation within each column shows that the greater mass of growth occurred in the upper part of the filter column where, according to the percent remaining vs. depth curves, the larger removal was effected. When the rates increased and the bottom part of the columns became more effective, a more even distribution of growth throughout the columns was observed.

Between the 30 mgad and 45 mgad rates there was a build-up of growth within each column. This is clearly indicated in Column I and to a lesser degree in Columns II and III. By the time the 60 mgad was reached, Column I was so thoroughly clogged that most of the fluid was running outside the column. For this reason Column I was taken out of action. Column II began to show less growth at this rate and Column III a great deal less. The flushing and shearing action of the great mass of liquid kept the lush growth which was observed at lower rates from accumulating.

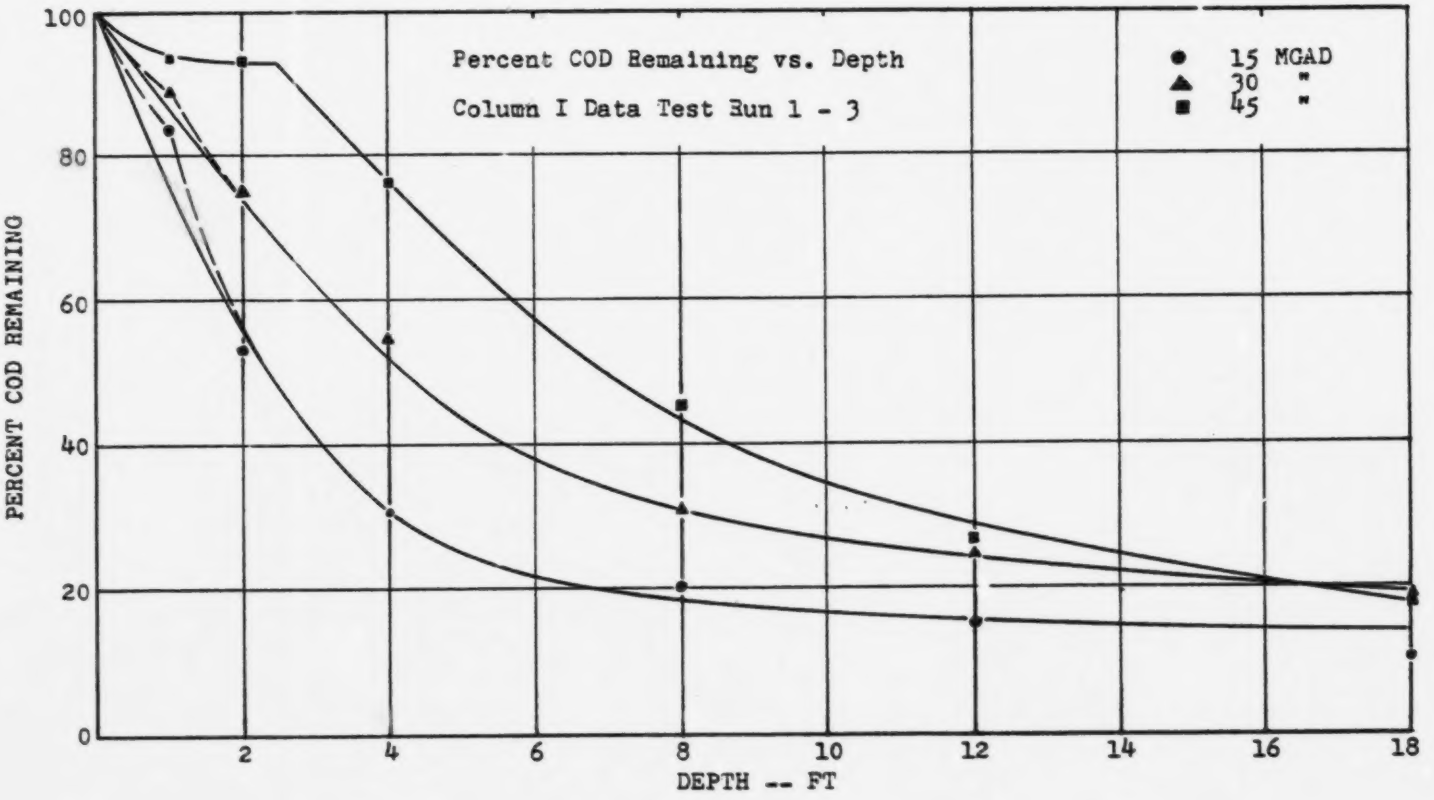

Percent COD Remaining vs. Depth
Column I Data Test Run 1 - 3
● 15 MGAD
▲ 30 "
■ 45 "
PERCENT COD REMAINING
100
80
60
40
20
0
2
4
6
8
10
12
14
16
18
DEPTH -- FT

FIG. 7

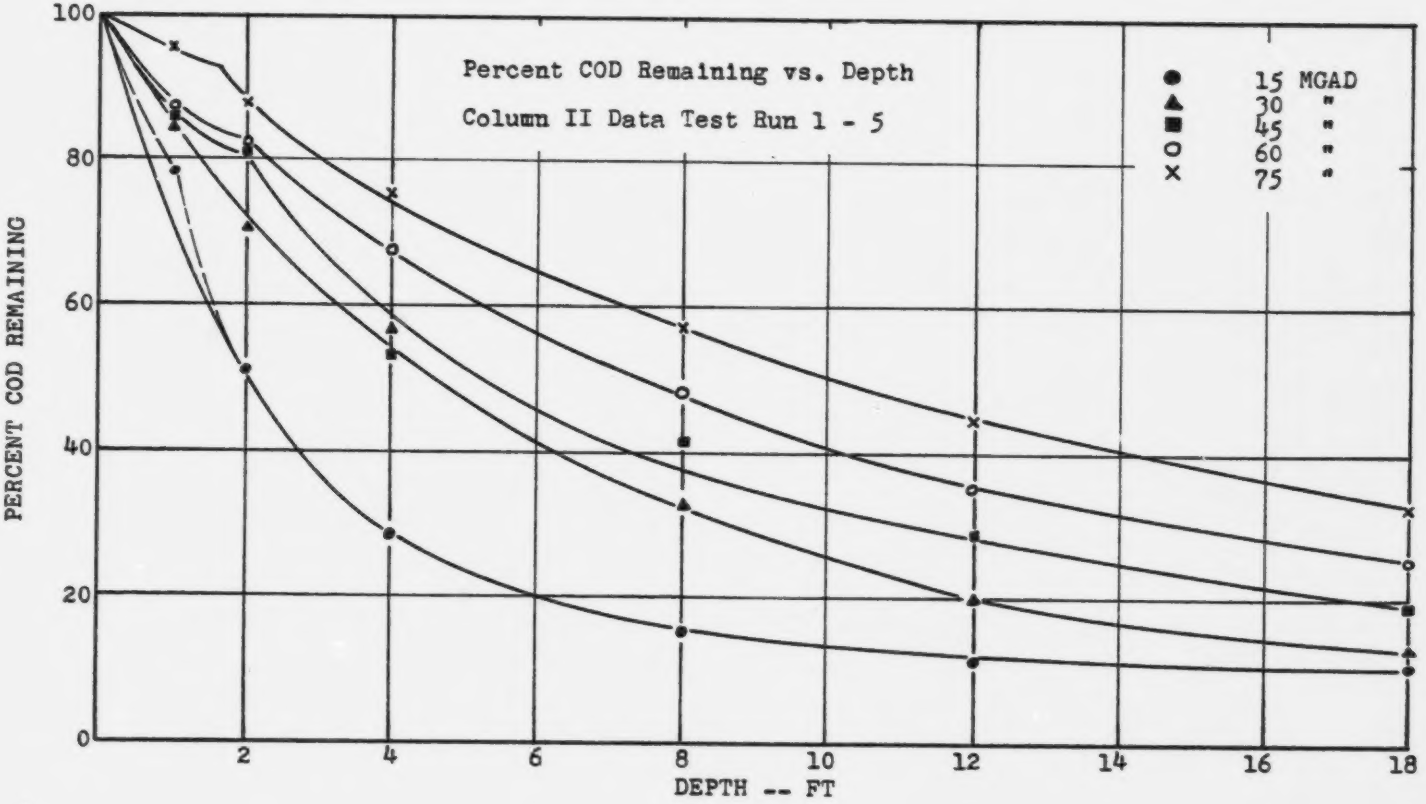

Percent COD Remaining vs. Depth
Column II Data Test Run 1 - 5
● 15 MGAD
▲ 30 "
■ 45 "
○ 60 "
× 75 "
PERCENT COD REMAINING
100
80
60
40
20
0
2
4
6
8
10
12
14
16
18
DEPTH -- FT

FIG. 8

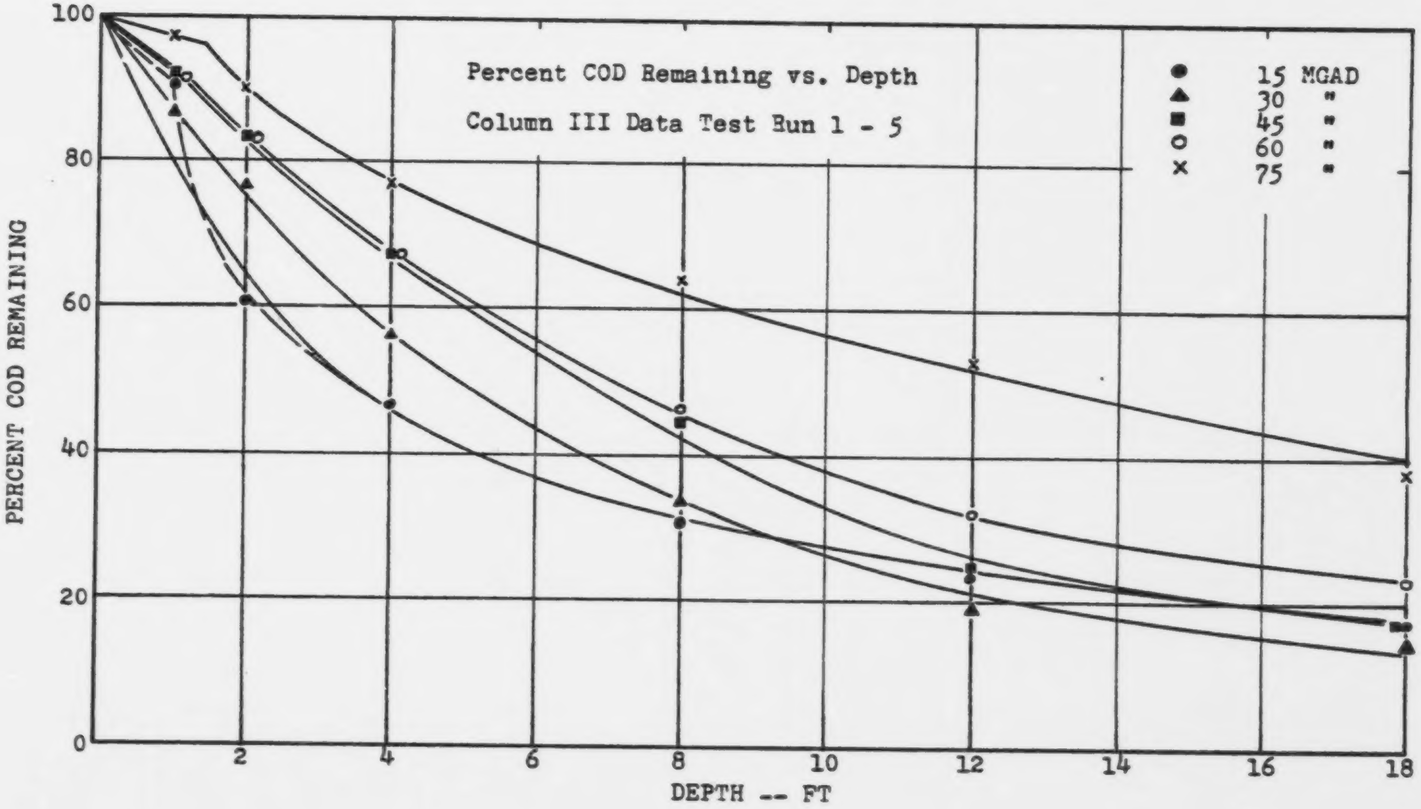

Percent COD Remaining vs. Depth
Column III Data Test Run 1 - 5
● 15 MGAD
▲ 30 "
■ 45 "
○ 60 "
× 75 "
PERCENT COD REMAINING
100
80
60
40
20
0
2
4
6
8
10
12
14
16
18
DEPTH -- FT

FIG. 9

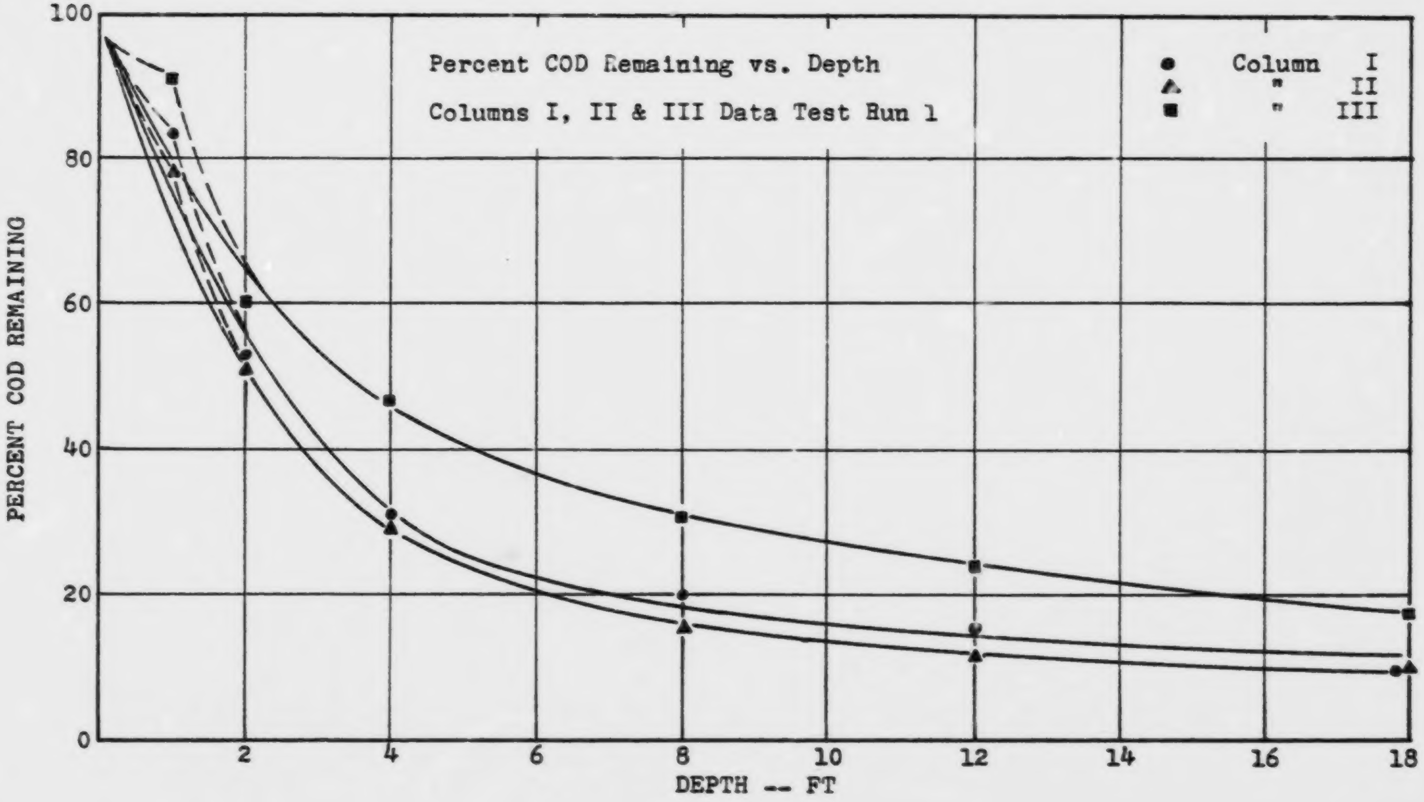

Percent COD Remaining vs. Depth
Columns I, II & III Data Test Run 1
● Column I
▲ " II
■ " III
PERCENT COD REMAINING
100
80
60
40
20
0
2
4
6
8
10
12
14
16
18
DEPTH -- FT

FIG. 10

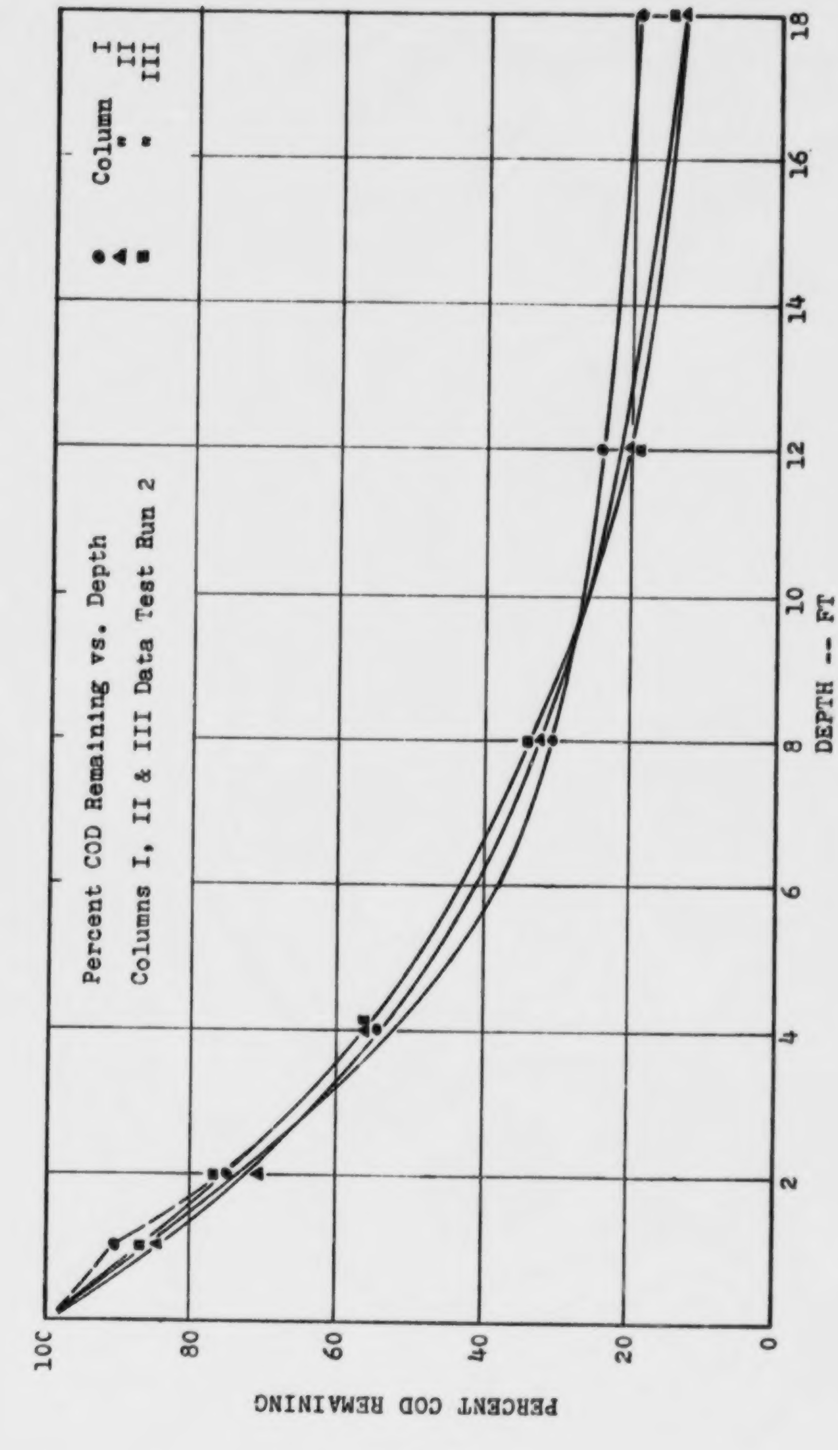

Percent COD Remaining vs. Depth
Columns I, II & III Data Test Run 2
● Column I
▲ " II
■ " III
PERCENT COD REMAINING
100
80
60
40
20
0
DEPTH -- FT
2
4
6
8
10
12
14
16
18

FIG. 11

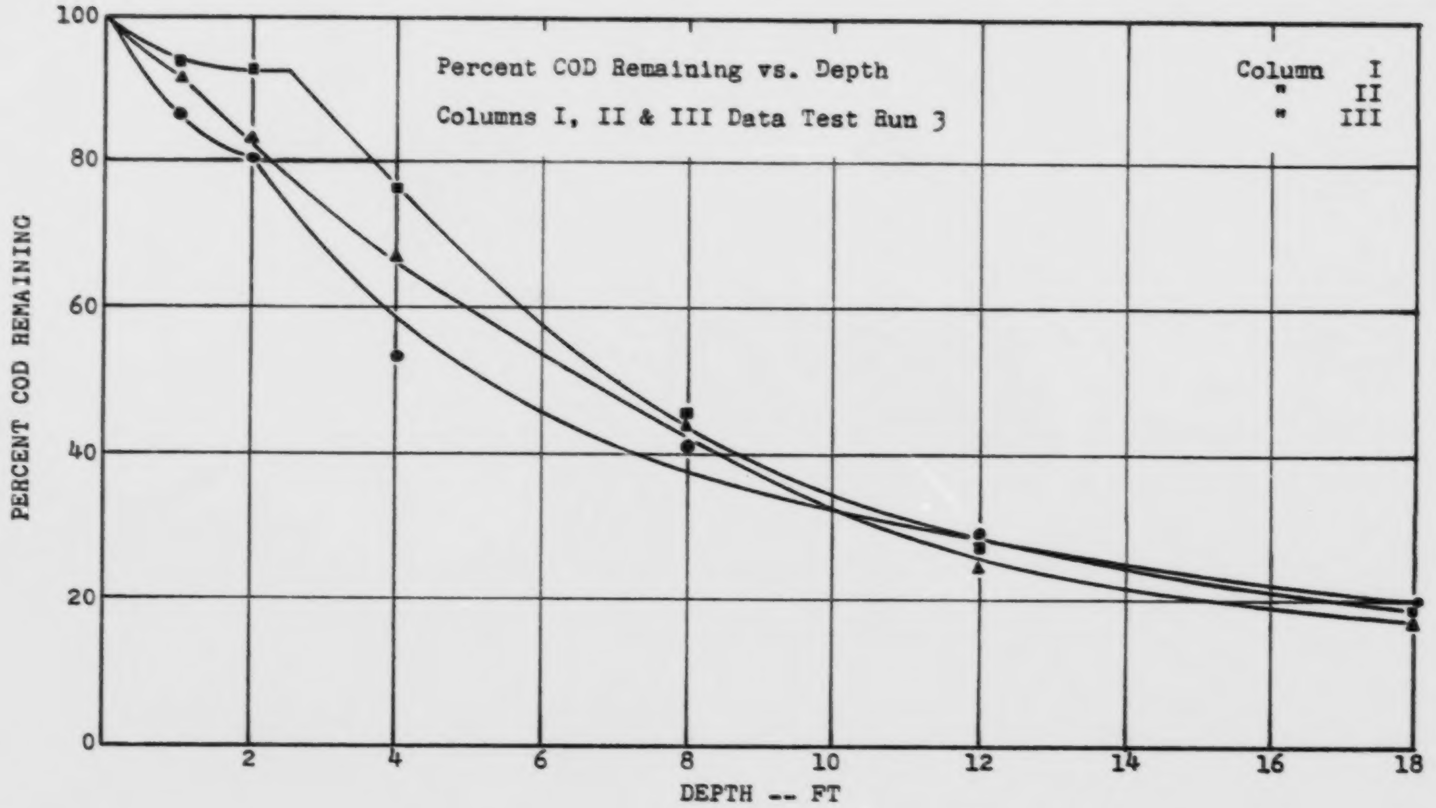
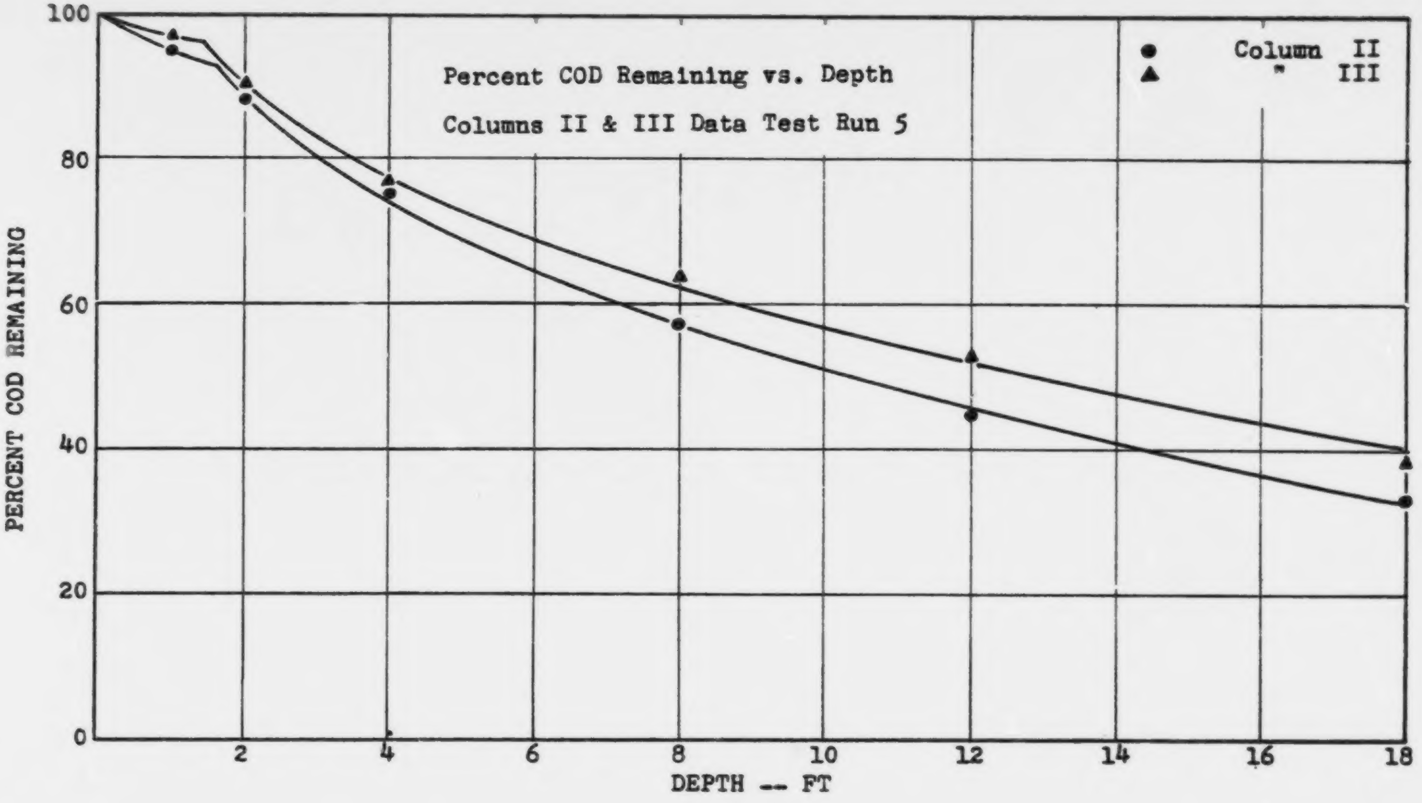

Percent COD Remaining vs. Depth
Columns I, II & III Data Test Run 3
Column I
" II
" III
PERCENT COD REMAINING
100
80
60
40
20
0
2
4
6
8
10
12
14
16
18
DEPTH -- FT

FIG. 12



Percent COD Remaining vs. Depth
Columns II & III Data Test Run 5
● Column II
▲ " III
PERCENT COD REMAINING
100
80
60
40
20
0
2
4
6
8
10
12
14
16
18
DEPTH -- FT

FIG. 13

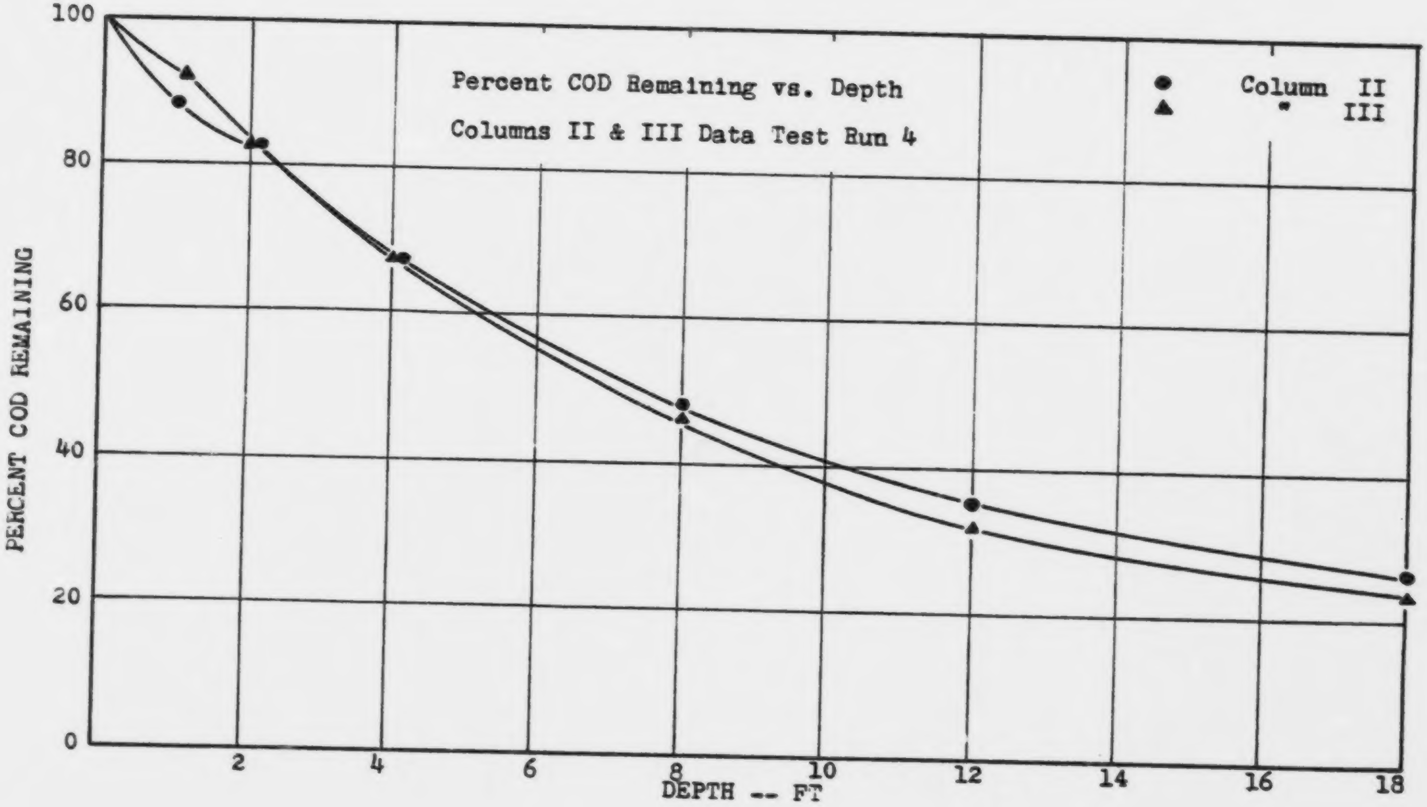

Percent COD Remaining vs. Depth
Columns II & III Data Test Run 4
● Column II
▲ " III
PERCENT COD REMAINING
100
80
60
40
20
0
2
4
6
8
10
12
14
16
18
DEPTH -- FT

FIG. 14

This action becomes even more evident at the 75 mgad rate where both Columns II and III have dropped to a relatively small biological mass which is now, however, more uniformly distributed.

From this we can draw the following conclusions. The mass of growth is not indicative of purification achieved. For the treatment effected by the columns at the higher rates in terms of pounds of organic material removed, it is almost four times greater than what was removed by a biological mass which was four times greater in volume. Thus, one-fourth the mass did four times more work. This does not contradict the localized differences in biological mass. The contention is that even though there was a great mass of growth concentrated in the area of great removal effectiveness, a much smaller mass could have effected the same thing. However, sloughing off and washing down of biological mass did not take place at the lower rates but accumulated as inactive sublayers which provided water storage capacity but little else.

The fact that the peaks of growth occur at the places of lowest ORP may bear out the view of Shapiro, which is that a low ORP can be indicative of greatest activity of biological mass. On the other hand, if the mass had come to the point where a lot of it is dead, then anaerobic conditions may be the cause of the low ORP.

Between columns the difference in surface area ratios comes into the picture. The ratios were computed to be 1.65 : 1 : 0.745 for Columns I, II and III, respectively. If this ratio is applied to the reported mass, then the same conclusions pertaining to mass of growth as having no influence on the purification achieved may be arrived at between columns as was done before within the columns.

Thus, the parameter of proper contact conditions seems to come into the foreground as being of greater influence than the relative biological mass which can be cultivated.

pH

In Fig. 18 several curves are plotted to show the pH variation with depth. Although influent and effluent pH are almost the same in most of the tests reported, there occurs a 10-fold increase and subsequent decrease in H^+ ions during the passage of the fluid through the filter column.

Accumulation of soluble waste products is the probable cause for this increase. The action of the CO_2 released during the degradation of the organic material could partially account for this pH increase. The H^+ ions build up during the rapid breakdown of the organic material in the substrate while passing through the upper portions of the filter column. CO_2 is given off and dissolved in the passing liquid, causing a rise in the H^+ ion concentration. Then, when the amount of CO_2 which is dissolving lessens

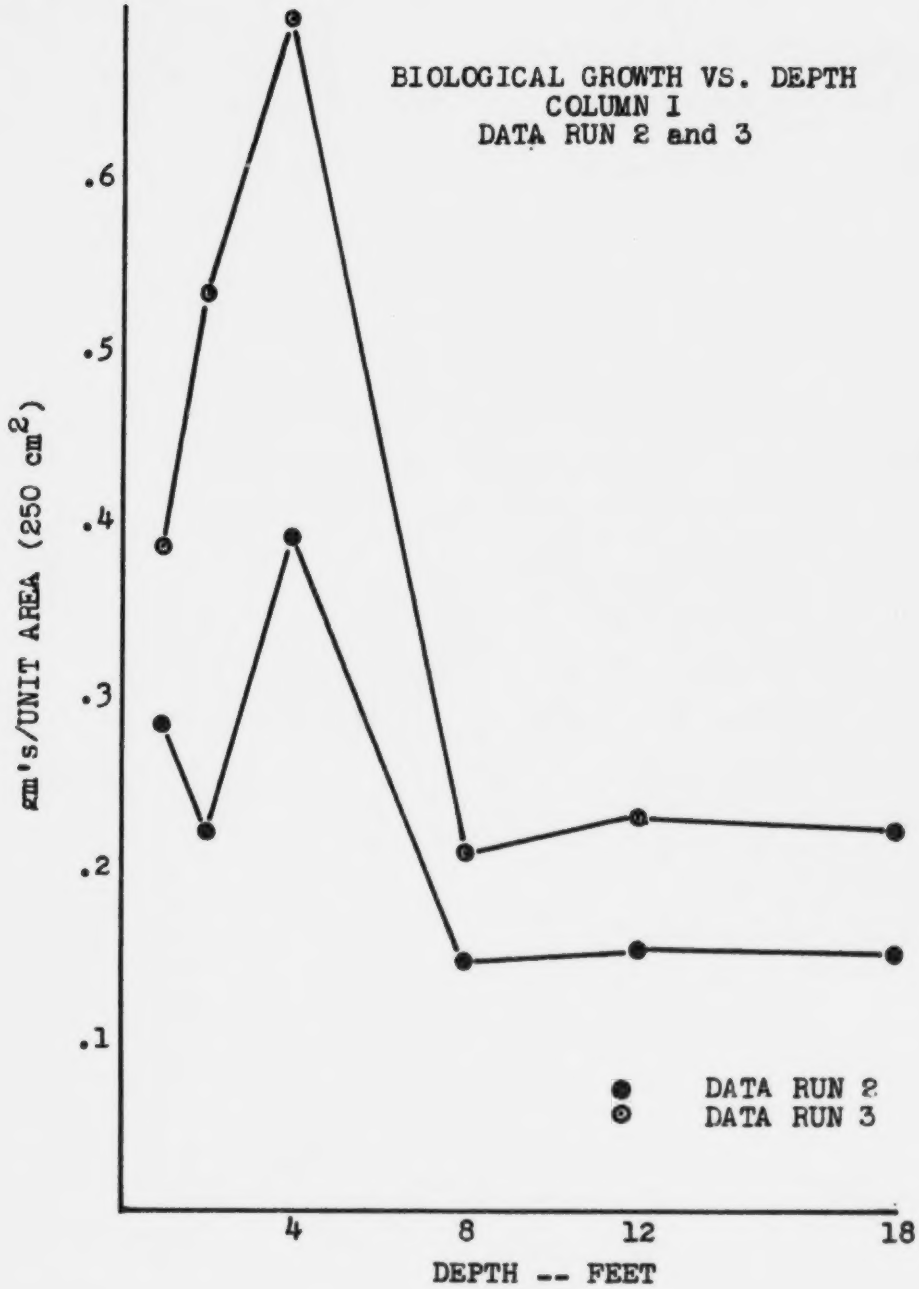
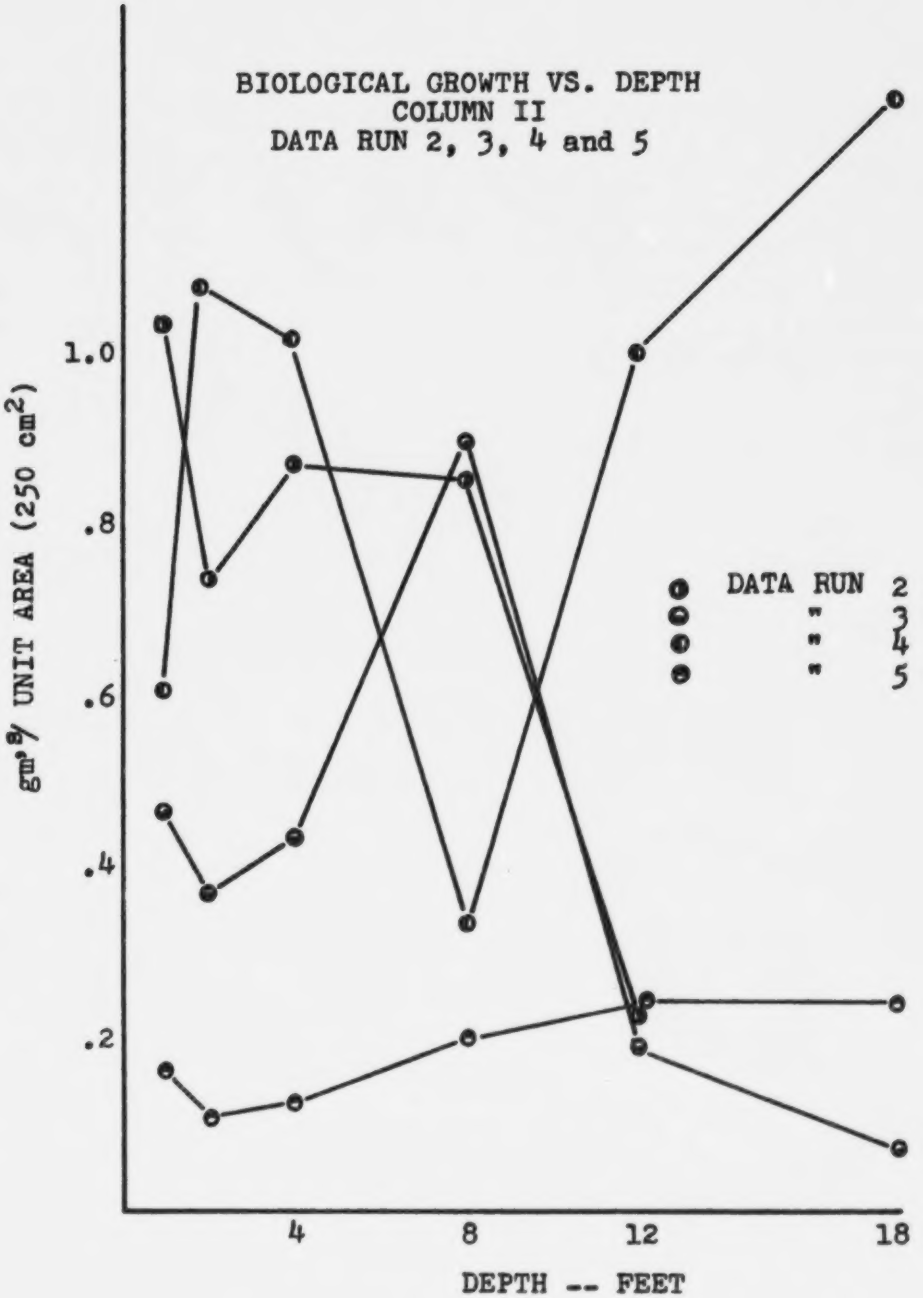

BIOLOGICAL GROWTH VS. DEPTH
COLUMN I
DATA RUN 2 and 3
gm's/UNIT AREA (250 cm^2)
.6
.5
.4
.3
.2
.1
● DATA RUN 2
⊙ DATA RUN 3
4
8
12
18
DEPTH -- FEET

FIG. 15



BIOLOGICAL GROWTH VS. DEPTH
COLUMN II
DATA RUN 2, 3, 4 and 5

FIG. 16

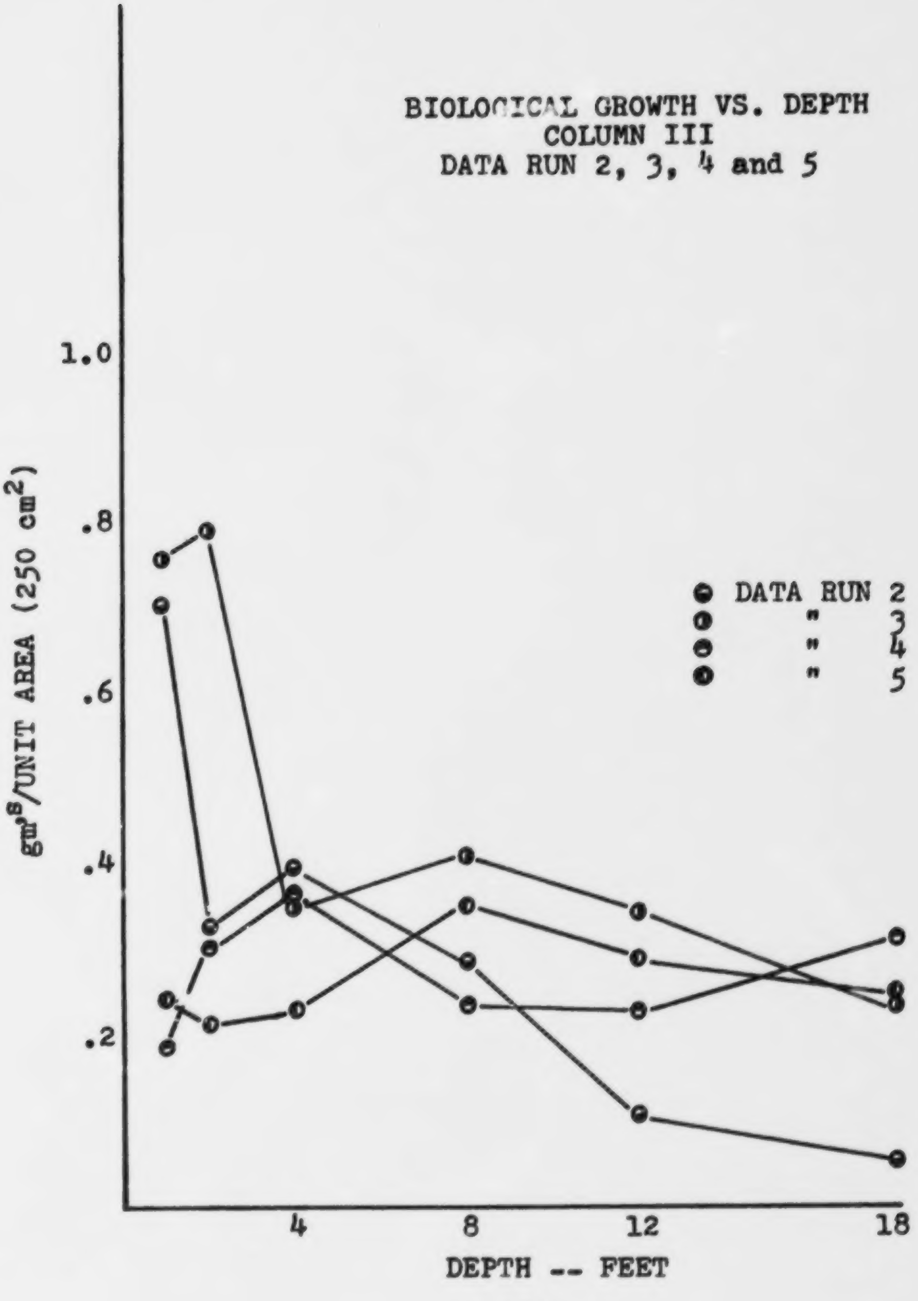

BIOLOGICAL GROWTH VS. DEPTH
COLUMN III
DATA RUN 2, 3, 4 and 5
● DATA RUN 2
● " 3
● " 4
● " 5
1.0
.8
.6
.4
.2
gm's/UNIT AREA (250 cm²)
4
8
12
18
DEPTH -- FEET

FIG. 17

and the CO_2 coming free as gas increases, helped by fluid turbulence, the pH rises again to a value comparable to influent pH at the bottom of the filter column.

The difference in pH values between columns can be explained by the relative size of the void spaces through which the fluid passes. In the smaller media the opportunity for the CO_2 to escape is much less than in the larger media where greater dripping and turbulence in contact with air give much better release conditions. The CO_2 thus remains entrained much longer in the filter column with the smaller media, resulting in a lower pH.

ORP

During the entire series of tests ORP readings were taken. The samples were collected and analyzed for ORP with a minimum delay of one to three minutes.

At the low rates a definite sag can be seen in the typical ORP curve, the minimum occurring between the one- and three-foot levels. The incoming substrate had an ORP which seemed to be temperature dependent, as the ORP was higher on the cooler days.

Since the largest part of the waste products is produced in the upper part of the filter column, it is to be expected that the largest amount of waste product oxidation needs to take place here, also.

As the substrate passed through the first section of the filter column, the ORP went down. This fact agrees

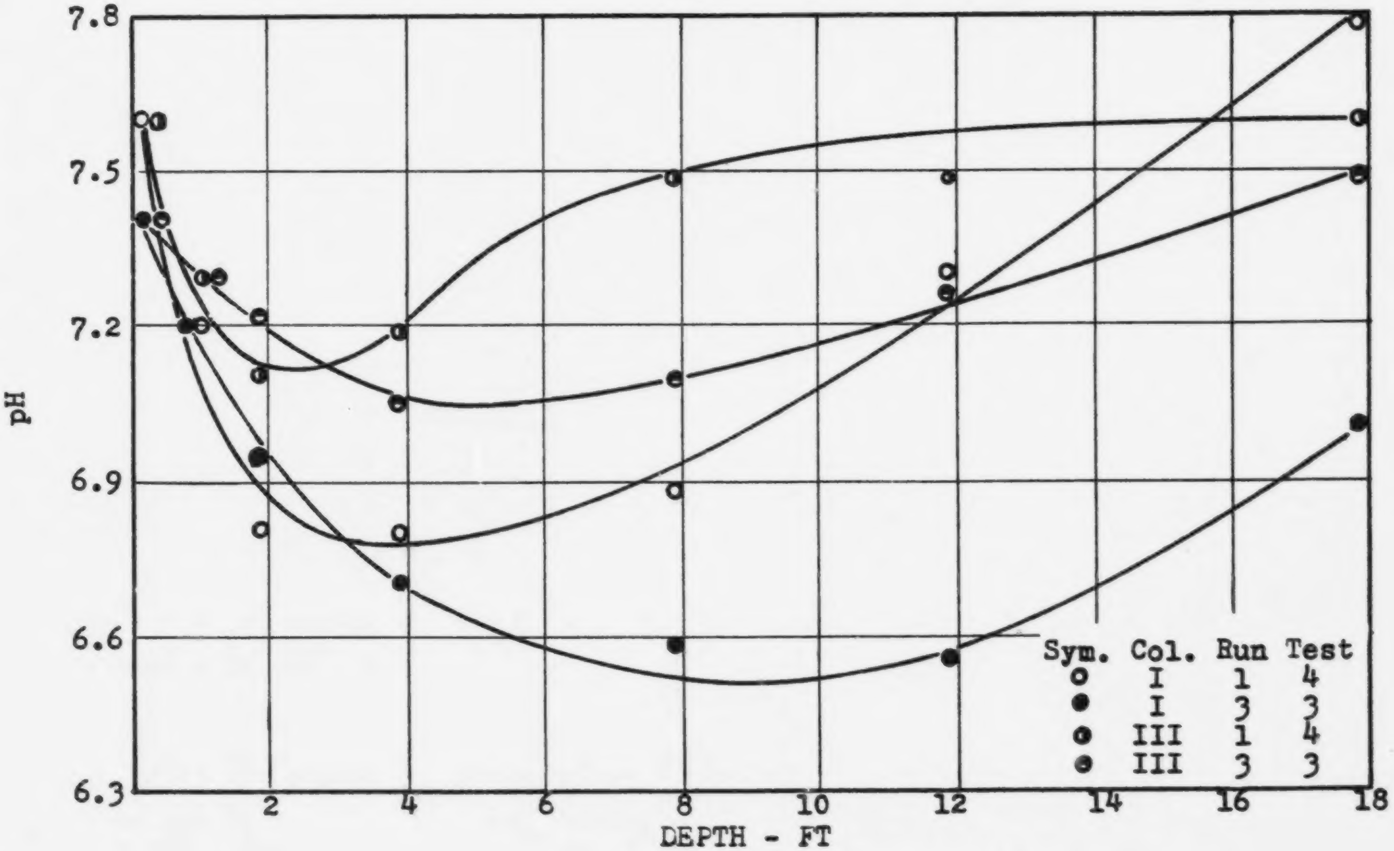


FIG. 18

TYPICAL CURVES
pH VS. DEPTH

with Shapiro's presentation of ORP, which states that the activation rate of dissolved oxygen lags the high production of reduced waste products which need to be oxidized, accounting for the ORP reduction.

Thus, the low ORP readings were not necessarily indicative of a process going anaerobic but more suggestive of a normally proceeding treatment process with a healthy culture. When the production of reduced waste products begin to abate in the middle portion of the filter column, the activation rate of oxygen begins to catch up and the ORP recovers, stabilizing in the bottom part to an equilibrium condition (Fig. 19).

At the higher rates, 60 and 75 mgad, there is less dip to the ORP vs. depth curve than at the lower rates. This is not quite in accord with the foregoing discussion as it might be expected that the relative proportion of the ORP in the substrate would be unaffected by the hydraulic loading rate. An examination of the percent remaining vs. depth curves may answer the problem. At the higher rates the curves are much flatter; thus, the relative proportion of ORP to waste products accumulated is more advantageous in maintaining a higher ORP because of less material to be oxidized vs. the activated oxygen available.

Cyclical fluctuations were noted during the test runs. If Shapiro's discussion of ORP is adhered to, then the reasons for these fluctuations can be limited to two basic parts of the process -- first, enzymes used in activating oxygen and, secondly, oxygen transfer from gaseous to liquid phase. If it is assumed that oxygen transfer during any one day of a test run was the same as any other day, then the enzyme activity is subject to variation. How is as yet a question mark. If, however, enzyme activity was constant, then the cause may lie with unequal aeration conditions. This latter view may have merit inasmuch as during reaeration the substrate (being a milky substance) gave rise to bubble formations in the sampling ports which may well have interferred with the reaeration capacity of the filter as a whole. The build-up of microbial growth may also have caused interference in reaeration within the column by clogging the interstices between the media.

The lack of subsequent reaeration may have diminished the bubble build-up and thus a cycle was established, parts of which were observed during data test runs.

The difference in ORP readings between Column I and Columns II or III may be attributed mainly to the lack of reaeration which in turn results from clogged media.

The lack of dissolved oxygen then retarding the activation of dissolved oxygen to activated oxygen and the progression of anaerobic conditions in the upper part of the trickling filter columns being the final effect and the cause of low ORP readings.

Thus, we may have a manifestation of both causes of low ORP. In Column I anaerobic conditions persist, and in Column III and perhaps also Column II healthy cultures produce reduced waste products in excess of the activated oxygen available.

Temperature

The temperature readings listed in the appendix indicate, more than anything else, the surrounding air temperature. Daily variations of about two degrees were observed during warm summer days.

The effect of temperature on the treatment process requires temperature control which is beyond the scope of the work here reported. The main reason for taking the temperature data was the possibility that there might be significant differences which would help in the analysis of the data.

SUMMARY

The research work reported in this thesis encompasses the testing for the influence of media size on the kinetics of the trickling filter process. The investigations included testing for COD, BOD, film quantity, pH, ORP and temperature. The results of these tests have been used to establish the influence of the media size upon the effectiveness of the biological process. The comparison

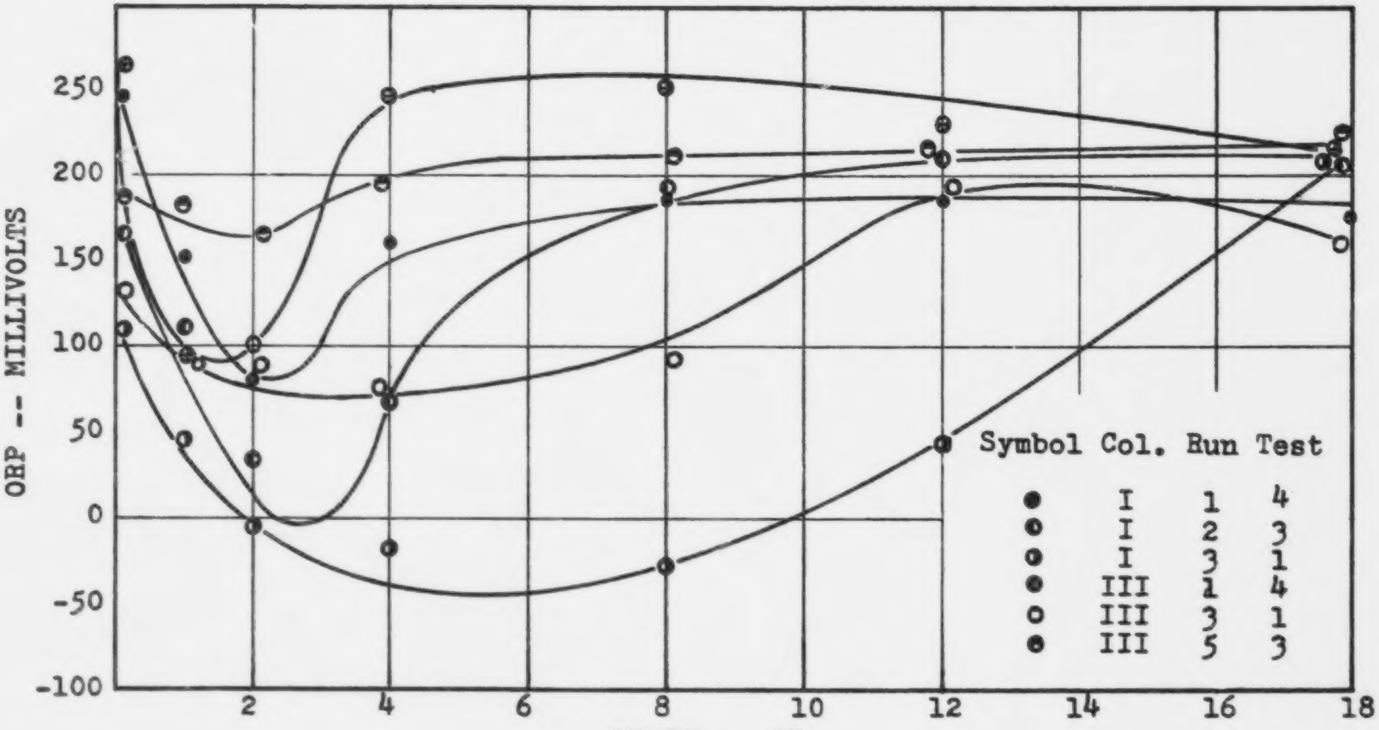


FIG. 19

TYPICAL CURVES
ORP VS. DEPTH

of columns by analysis of variance of the COD and BOD data showed that the largest percent of purification is accomplished in the upper eight feet of the filter columns. As the hydraulic rates are increased, greater use is made of the lower portion of the column. The rate constant K may thus be expected to vary with hydraulic loadings. Column I was shown to have the least capacity to purify the waste used in these tests when the rates were increased. The clogging and ponding which caused near anaerobic conditions made it necessary to discontinue testing of Column I, after 45 mgad rate testing was completed. Columns II and were almost the same in their capacity to handle the hydraulic and organic loadings and in effecting a degree of treatment. From a general review and acquaintance with the entire project, the author feels that Column III displayed the best filter column characteristics in terms of operational problems encountered.

A problem which has not been mentioned heretofore is the difference between BOD and COD values obtained from tests which were prepared from the same sample. The COD removal effected by any of the filter columns was always greater in terms of percent removed than the BOD removal. The reason for this is not understood except the general conclusion that the COD test does not remove certain constituents which are removed in the BOD test.

Film quantity was shown to be of no influence upon purification capacity. Growth which developed became an inactive mass and only the outer film layers were considered active in the purification process.

A pH drop due to the dissolving of waste products, probably CO_2, was observed throughout the series of tests. The recovery to at least the influent pH was attributed to the release of CO_2 from the fluid mass helped by turbulence in contact with air when the rate of CO_2 uptake and release passed a maximum around the four-foot depth. The difference between media size accounts for the release condition for the CO_2. The larger media sizo provides better opportunity for turbulence and air surface contact.

The characteristic ORP sag was accounted for by the two reactions which are considered to take place -- first, the activation of dissolved oxygen and, secondly, the oxidation of reduced waste products by the activated oxygen. The rate by which activation lags the oxidation of excess waste products of a healthy culture was considered as causitive of the characteristic ORP drop observed. The rate of activation was considered dependent on enzymatic activity and oxygen transfer from gaseous to liquid state. The ORP differences noted between the three columns appear to be due to the oxygen transfer conditions and the release of gaseous waste products which tend to reduce the ORP. The larger media favored the ORP conditions.

Temperature variation within the range reported was not of such magnitude that conclusions may be made about its influence upon the treatment processes.

CONCLUSIONS

1. The 9/16-inch media is impractical as the clogging and ponding problem will cause system failure at any hydraulic rate. Only regular remedial action permitted continuation of testing.

2. The 7/8-inch and 1-1/4-inch marbles are both effective as media and more so as the hydraulic rates are increased. A maximum hydraulic rate using all the available pore space as fluid passage would be a limiting factor in the rate of application.

3. The difference between the 7/8-inch and 1-1/4-inch media is negligible when the variation of the observations is subjected to analysis of variance and the 90 percent significance level is used.

4. The limiting practical depth at rates below 30 mgad is about eight feet.

5. High rates make greater use of the filter portion below eight feet.

6. The K rates are considered as dependent upon hydraulic rates.

7. Total film quantities are of no influence in the degree of purification achieved. Some stratification with depth will occur, depending upon where the greatest organic removal was effected; i.e., there are no organisms where little is left to be removed.

8. The pH will drop with depth due to uptake of waste products. Release of gaseous waste products will cause pH to recover.

9. A negative or low ORP value is not necessarily indicative of a failing biological process but in healthy cultures represents a lag between activation of dissolved oxygen and oxidation of reduced metabolic waste products.

SUGGESTIONS FOR FUTURE RESEARCH

1. The hydraulic rate limits for a particular media size which will maintain adequate degrees of treatment.

2. The optimum contact and film conditions for a trickling filter system.

3. Further investigations of ORP relating it to dissolved oxygen, metabolic activity of the organisms and gas analysis of the surrounding air mass.

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APPENDICES

APPENDIX A

ANALYSIS OF VARIANCE FROM COD DATA

ANALYSIS OF VARIANCE FROM BOD DATA

VALUES OF FISHER'S F
OBTAINED BY ANALYSIS OF VARIANCE
OF COD DATA FOR FILTER COLUMNS I, II AND III

	RUN		
DEPTH	1	2	3
1	12.97	3.52	0.356
2	0.142	0.222	2.182
4	29.71	0.634	3.32
8	11.33	0.39	2.484
12	7.64	23.07	4.73
18	1.59	7.55	22.12

DATA TEST RUN	F VALUE	d.f.	SIGN. LEVEL, %
1 and 2	3.35	2 and 27	5
3	3.89	2 and 12	5

VALUES OF FISHER'S F
OBTAINED BY ANALYSIS OF VARIANCE
OF COD DATA FOR FILTER COLUMNS I AND II

	RUN		
DEPTH	1	2	3
1	12.25	7.89	0.63
2	0.14	0.42	1.33
4	0.27	1.08	0.006
8	5.61	0.004	3.97
12	7.79	38.88	2.97
18	0.79	13.99	34.93

DATA TEST RUN	F VALUE	d.f.	SIGN. LEVEL, %
1 and 2	4.21	1 and 27	5
3	4.75	1 and 12	5

VALUES OF FISHER'S F
OBTAINED BY ANALYSIS OF VARIANCE
OF COD DATA FOR FILTER COLUMNS I AND III

	RUN		
DEPTH	1	2	3
1	140.83	1.07	0.408
2	0.025	0.04	0.87
4	32.51	0.8	4.92
8	5.71	0.655	3.46
12	0.94	29.7	9.41
18	2.77	7.76	31.34

DATA TEST RUN	F VALUE	d.f.	SIGN. LEVEL, %
1 and 2	4.21	1 and 27	5
3	4.75	1 and 12	5

VALUES OF FISHER'S F
OBTAINED BY ANALYSIS OF VARIANCE
OF COD DATA FOR FILTER COLUMNS II AND III

	RUN				
DEPTH	1	2	3	4	5
1	236.11	2.51	0.025	1.18	0.48
2	2.76	0.72	4.34	1.067	0.25
4	53.94	0.02	5.03	0.02	0.086
8	22.65	0.604	0.17	0.404	4.29
12	14.17	0.61	1.81	1.98	8.16
18	1.91	0.91	0.10	3.416	6.08

DATA TEST RUN	F VALUE	d.f.	SIGN. LEVEL, %
1 and 2	4.21	1 and 27	5
3	4.75	1 and 12	5
4 and 5	5.32	1 and 8	5

VALUES OF FISHER'S F
OBTAINED BY ANALYSIS OF VARIANCE
OF BOD DATA FOR FILTER COLUMNS I, II AND III

	RUN				
DEPTH	1	2	3	4	5
4	1.98	1.27	0.167	1.48	0.107
8	11.38	3.86	37.0	2.44	0.037
12	3.72	20.86	102.83	9.92	0.72
18	0.89	12.2	267.0	2.59	2.48

DATA TEST RUN	F VALUE	d.f.	SIGN. LEVEL, %
1, 2 and 3	5.14	2 and 6	5
4 and 5	7.71	1 and 4	5

VALUES OF FISHER'S F
OBTAINED BY ANALYSIS OF VARIANCE
OF BOD DATA FOR FILTER COLUMNS I AND II

	RUN		
DEPTH	1	2	3
4	3.9	2.18	0
8	22.1	1.69	45
12	4.83	22.3	132
18	0.0234	21.7	392

DATA TEST RUN	F VALUE	d.f.	SIGN. LEVEL, %
1, 2 and 3	5.99	1 and 6	5

VALUES OF FISHER'S F
OBTAINED BY ANALYSIS OF VARIANCE
OF BOD DATA FOR FILTER COLUMNS I AND III

	RUN		
DEPTH	1	2	3
4	1.43	1.45	0.278
8	9.2	7.72	64.2
12	0.107	13.1	173.5
18	1.49	38.5	408.0

DATA TEST RUN	F VALUE	d.f.	SIGN. LEVEL, %
1, 2 and 3	5.99	1 and 6	5

VALUES OF FISHER'S F
OBTAINED BY ANALYSIS OF VARIANCE
OF BOD DATA FOR FILTER COLUMNS II AND III

	RUN				
DEPTH	1	2	3	4	5
4	0.61	0.091	0.278	1.48	0.107
8	2.78	2.2	1.67	2.44	0.037
12	6.3	1.25	2.85	9.92	0.72
18	1.14	2.4	0.161	2.59	2.48

DATA TEST RUN	F VALUE	d.f.	SIGN. LEVEL, %
1, 2 and 3	5.99	1 and 6	5
4 and 5	7.71	1 and 4	5

APPENDIX B

SUMMARY OF EXPERIMENTAL DATA

1. FILM GROWTH
2. pH
3. ORP
4. TEMPERATURE

SUMMARY DATA

GROWTH/UNIT SURFACE AREA

RUN 2

BIOLOGICAL MASS IN gms. (DRY)

	COL. I	COL. II	COL. III
NUMBER OF SPHERES	40	15	8
DEPTH			
1	.2812	.4644	.7055
2	.2198	.3705	.3285
4	.3906	.4359	.3960
8	.1467	.8961	.2879
12	.1502	.1892	.1071
18	.1486	.0732	.0597

SUMMARY DATA

GROWTH/UNIT SURFACE AREA

RUN 3

BIOLOGICAL MASS IN gms. (DRY)

	COL. I	COL. II	COL. III
NUMBER OF SPHERES	40	15	8
DEPTH			
1	.3844	1.0321	.7566
2	.5335	.7383	.7874
4	.6910	.8705	.3503
8	.2084	.8522	.4088
12	.2290	.2261	.3423
18	.2196		.2340

SUMMARY DATA

GROWTH/UNIT SURFACE AREA

Run 4

BIOLOGICAL MASS IN gms. (DRY)

		COL. II	COL. III
NUMBER OF SPHERES		15	8
DEPTH			
1		.6048	.1935
2		1.0755	.3043
4		1.0165	.3696
8		.3354	.2373
12		.9971	.2301
18		1.2968	.3130

SUMMARY DATA

GROWTH/UNIT SURFACE AREA

RUN 5

BIOLOGICAL MASS IN gms. (DRY)

		COL. II	COL. III
NUMBER OF SPHERES		15	8
DEPTH			
1		.1830	.2426
2		.1117	.2152
4		.1283	.2317
8		.2034	.3522
12		.2446	.2905
18		.2418	.2537

SUMMARY DATA

pH VALUES

RUN 1

DEPTH	COL. I					COL. II					COL. III				
	TEST					TEST					TEST				
	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
0		6.9	7.4	7.6	7.5	7.3		7.5	7.7	7.8	7.2	8.0	7.6	7.6	7.7
1	6.6	7.0	7.2	7.2	6.9	6.8		7.2	7.2	7.5	6.7	7.6	7.4	7.3	7.4
2	6.5	6.7	6.9	6.8	6.6	6.7		7.0	7.1	7.2	6.5	7.3	7.0	7.1	7.3
4	6.4	6.3	6.6	6.8	6.5	6.8		7.0	7.0	7.3	6.5	7.2	7.2	7.2	7.5
8	6.3	6.4	6.9	6.9	6.8	7.1		7.5	7.6	7.8	6.9	7.2	7.5	7.5	7.6
12	6.7	6.9	7.3	7.3	7.2	7.3		7.6	7.7	7.9	7.5	7.3	7.5	7.5	7.6
18	7.0	7.4	7.5	7.8	7.5	7.3		7.9	7.5	7.8	7.4	7.5	7.8	7.6	7.7

SUMMARY DATA

pH VALUES

RUN 2

DEPTH	COL. I					COL. II					COL. III				
	TEST					TEST					TEST				
	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
0	7.8	7.6	7.5	7.8	7.6	7.8	7.6	7.8	7.8	7.6	7.9	7.6	7.6	7.8	7.4
1	7.4	7.5		7.3	7.3	7.4	7.1	7.4	7.4	7.3	7.5	7.3	7.3	7.4	6.8
2	7.2	7.3	6.9	6.9	7.0	7.2	6.9	7.0	7.0	7.1	7.4	7.2	7.1	7.3	7.1
4	7.0	6.6	6.5	6.7	6.8	7.1	6.8	6.8	6.9	7.0	7.4	7.0	6.9	7.1	6.8
8	7.3	6.4	6.5	6.6	6.8	7.1	6.8	6.9	6.8	7.0	7.6	7.2	7.2	7.3	7.2
12	7.4	6.7	6.6	6.9	6.9	7.4	7.3	7.2	7.2	7.3	7.6	7.3	7.2	7.4	7.4
18	7.8	7.4	7.3	7.3	7.4	7.6	7.5	7.9	7.9	7.6	7.5	7.5	7.4	7.6	7.1

SUMMARY DATA

pH VALUES

RUN 3

DEPTH	COL. I					COL. II					COL. III				
	TEST					TEST					TEST				
	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
0	7.7	7.6	7.4	7.6	7.5		7.6	7.4	7.6	7.5	7.7	7.6	7.4	7.6	7.5
1	7.2	7.2	7.2	7.4	7.1		7.3	7.2	7.4	7.2	7.3	7.3	7.3	7.2	7.1
2	7.1	7.0	7.0	7.1	6.9		7.1	7.0	7.3	6.9	7.2	7.2	7.2	7.2	6.9
4	6.9	6.7	6.7	6.9	6.6		6.9	6.9	7.1	6.7	7.1	7.1	7.1	7.2	6.9
8	6.5	6.3	6.6	6.7	6.3		6.8	6.8	6.9	6.6	7.2	7.2	7.1	7.3	7.0
12	6.6	6.5	6.6	6.7	6.4		6.7	7.0	6.9	6.7	7.3	7.4	7.3	7.3	7.2
18	6.8	6.7	7.0	6.8	6.8		7.3	7.2	7.4	7.2	7.5	7.6	7.5	7.5	7.4

SUMMARY DATA

pH VALUES

RUN 4

DEPTH		COL. II					COL. III				
		TEST					TEST				
		1	2	3	4	5	1	2	3	4	5
0		7.4	7.4	7.6	7.7	7.7	7.4	7.4	7.6	7.7	7.7
1		7.3	7.2	7.3	7.3	7.4	7.2	7.3	7.5	7.5	7.4
2		7.1	7.1	7.0	7.2	7.3	6.8	7.2	7.2	7.3	7.2
4		7.0	7.1	6.9	6.9	7.0	6.7	6.9	7.0	7.1	7.0
8		7.0	7.0	6.6	6.8	6.9	6.8	7.0	6.9	7.1	6.8
12		7.2	7.2	6.8	6.9	6.8	7.0	7.0	7.0	7.1	7.0
18		7.5	7.5	7.0	7.0	7.1	7.3	7.3	7.4	7.6	7.8

SUMMARY DATA

pH VALUES

RUN 5

DEPTH		COL. II					COL. III				
		TEST					TEST				
		1	2	3	4	5	1	2	3	4	5
0		7.6	7.6	7.5	7.5	7.7	7.6	7.6	7.5	7.5	7.7
1		7.4	7.5	7.3	7.2	7.6	7.3	7.5	7.5	7.4	7.6
2		7.2	7.3	7.2	7.1	7.3	7.3	7.3	7.3	6.9	7.6
4		6.9	7.0	7.0	6.9	7.2	7.2	7.2	7.2	6.9	7.4
8		6.7	6.9	6.8	6.7	7.0	7.1	7.0	7.2	7.2	7.4
12		6.7	6.8	6.8	6.7	6.9	7.1	7.2	7.3	7.2	7.3
18		7.0	7.0	6.9	6.9	7.1	7.4	7.5	7.3	7.4	7.5

SUMMARY DATA

ORP VALUES

RUN 1

DEPTH	COL. I					COL. II					COL. III				
	TEST					TEST					TEST				
	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
0		250	260	245	165			240	235	250		245	235	265	255
1		200	200	150	15			160	130	185		220	82	95	140
2		210	140	80	-165			90	165	180		170	45	100	135
4		205	220	160	30			150	140	160		165	120	245	240
8		260	250	190	190			210	235	230		245	175	250	220
12		260	235	185	227			215	220	205		220	200	230	235
18		235	255	175	180			245	195	175		220	225	205	245

SUMMARY DATA

ORP VALUES

RUN 2

DEPTH	COL. I					COL. II					COL. III				
	TEST					TEST					TEST				
	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
0	140	190	165	120	150	185	195	210	205	180	215	190	210	215	130
1	80	65	110	10	90	100	90	150	105	100	185	135	155	100	-35
2	15	25	-5	-90	-80	60	90	175	130	105	205	160	155	90	-55
4	20	-125	65	-70	115	170	140	220	160	155	220	190	205	110	30
8	30	50	190	-95	95	215	165	245	205	170	230	180	230	220	80
12	70	208	210	40	140	215	200	220	215	210	215	225	235	225	175
18	148	230	205	215	208	180	200	190	215	190	200	215	225	215	165

SUMMARY DATA

ORP VALUES

RUN 3

DEPTH	COL. I					COL. II					COL. III				
	TEST					TEST					TEST				
	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
0	110	90	85	55	45	100		80	55	45	130		80	55	40
1	45	40	5	55	-40	20	105	40	90	-40	90	95	65	60	-25
2	35	35	-15	35	-95	0	100	20	80	-55	85	105	70	65	-10
4	-20	0	-85	0	-105	0	100	0	40	-50	70	100	60	65	-15
8	-30	-140	-120	-170	-150	70	90	-5	30	-45	90	85	45	95	-7
12	45	20	-50	25	-125	175	60	85	120	0	195	75	100	120	45
18	205	250	170	175	100	193	175	170	175	105	160	320	170	175	130

SUMMARY DATA

ORP VALUES

RUN 4

DEPTH		COL. II					COL. III				
		TEST					TEST				
		1	2	3	4	5	1	2	3	4	5
0		115	175	170	145	170	115	175	170	145	170
1		95	170	150	120	130	120	140	120	140	120
2		145	170	170	160	120	135	150	160	145	125
4		165	190	195	185	165	140	195	170	160	170
8		185	225	210	190	210	170	205	200	170	200
12		185	245	220	205	225	170	220	210	180	210
18		185	235	220	200	225	170	215	190	180	190

SUMMARY DATA

ORP VALUES

RUN 5

DEPTH		COL. II					COL. III				
		TEST					TEST				
		1	2	3	4	5	1	2	3	4	5
0		210	185	185	145	125	210	180	185	145	125
1		160	130	150	80	20	205	180	180	145	130
2		185	140	115	65	10	215	185	165	160	145
4		175	155	115	75	-100	220	170	195	160	130
8		230	185	155	205	130	230	205	210	190	190
12		265	215	225	200	170	245	205	210	200	200
18		260	220	250	230	215	250	205	215	185	190

101<

SUMMARY DATA

TEMPERATURE VALUES

RUN 1

DEPTH	COL. I					COL. II					COL. III				
	TEST					TEST					TEST				
	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
0		17.9	18.9	16.0	19.4	20.2		19.6	21.2	19.0	20.7	17.8	21.2	20.2	18.0
1	16.6	18.1	18.9	17.0	19.6	20.1		19.5	21.2	19.0	20.9	18.0	21.3	20.3	18.5
2	17.4	18.2	19.3	18.0	19.6	20.2		19.6	21.2	19.0	21.0	18.2	22.5	20.3	19.5
4	17.8	18.2	19.6	19.5	20.1	20.4		19.6	21.2	19.0	20.9	18.3	22.5	20.5	20.0
8	17.6	18.2	19.6	21.0	20.5	19.7		18.3	21.5	19.3	20.2	18.0	22.5	20.5	21.8
12	17.6	18.2	19.4	20.0	20.7	19.2		18.2	21.1	19.5	19.8	17.1	22.2	20.2	22.0
18	17.6	18.5	18.9	20.0	20.5	19.2		18.1	21.5	19.5	19.3	18.2	22.2	19.8	22.2

SUMMARY DATA

TEMPERATURE VALUES

RUN 2

DEPTH	COL. I					COL. II					COL. III				
	TEST					TEST					TEST				
	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
0	21.0	22.5	21.0	23.5	22.0	22.0	22.5	21.0	20.0	22.0	23.0	22.5	22.5	20.0	23.0
1	21.5	22.5	21.0	23.5	22.0	22.5	22.5	21.0	20.5	22.0	23.0	22.5	22.5	20.0	23.5
2	21.0	22.0	21.0	24.0	22.0	22.5	22.0	21.0	20.5	22.5	23.0	22.5	23.0	20.5	24.0
4	21.5	22.0	21.0	24.0	22.0	22.5	22.0	21.0	21.0	23.0	23.0	22.5	22.5	20.5	24.0
8	21.5	22.0	20.5	24.0	22.0	22.0	22.0	21.0	21.0	23.0	23.0	21.5	22.0	21.0	24.0
12	21.0	21.5	20.0	23.5	21.0	22.0	21.5	21.0	21.0	22.0	22.5	21.5	22.0	21.0	23.0
18	21.0	21.0	20.0	24.0	22.0	21.5	21.0	21.0	21.0	22.0	22.5	21.0	22.5	21.0	24.0

SUMMARY DATA

TEMPERATURE VALUES

RUN 3

DEPTH	COL. I					COL. II					COL. III				
	TEST					TEST					TEST				
	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
0	22.5	22.0	22.0	22.0	23.0	24.5		22.0	22.0	23.0	25.0		22.0	22.0	
1	22.5	22.0	22.0	22.0	23.0	24.5	22.0	22.0	22.0	23.0	25.0	22.0	22.0	22.0	23.0
2	22.5	22.0	22.0	22.0	23.0	24.5	22.0	22.0	22.0	23.0	25.0	22.0	22.0	22.0	23.0
4	22.5	22.0	22.0	22.0	23.0	24.5	22.0	21.5	22.0	23.0	25.0	22.0	21.5	22.0	23.0
8	22.0	21.5	21.5	22.0	22.5	24.5	21.5	21.5	21.5	22.5	25.0	21.8	21.5	21.5	22.5
12	21.5	21.0	21.5	21.5	22.5	24.0	21.5	21.5	21.5	22.5	25.0	21.5	21.5	21.5	22.0
18	21.0	21.0	21.0	21.5	22.0	24.0	21.0	21.0	21.0	22.0	25.0	21.0	21.0	21.0	22.0

SUMMARY DATA

TEMPERATURE VALUES

RUN 4

DEPTH		COL. II					COL. III				
		TEST					TEST				
		1	2	3	4	5	1	2	3	4	5
0		22.0	22.5	23.0	22.0	22.0	22.0	22.5	23.0	22.0	22.0
1		22.0	22.5	23.0	21.5	22.0	22.0	22.5	23.0	22.0	22.0
2		22.0	22.5	23.0	21.5	22.0	22.0	22.5	23.0	22.0	22.0
4		22.0	22.0	23.0	21.5	22.0	22.0	22.0	23.0	22.0	22.0
8		21.5	22.0	23.0	21.5	22.0	21.5	22.0	23.0	22.0	22.0
12		21.0	21.5	22.5	21.5	22.0	21.0	21.5	22.5	22.0	22.0
18		21.0	21.5	22.0	21.5	22.0	21.0	21.5	22.0	21.5	22.0

SUMMARY DATA

TEMPERATURE VALUES

RUN 5

DEPTH		COL. II					COL. III				
		TEST					TEST				
		1	2	3	4	5	1	2	3	4	5
0		20.5	19.5	20.2	20.0	20.2	20.5	19.5	20.2	20.0	20.2
1		20.5	19.5	20.2	20.0	20.2	20.5	19.5	20.2	20.0	20.2
2		20.5	19.5	20.2	20.0	20.2	20.5	19.5	20.2	20.0	20.2
4		20.5	19.5	20.1	20.0	20.0	20.5	19.4	20.1	20.0	20.0
8		20.3	19.4	20.1	19.8	20.0	20.3	19.4	20.1	19.8	20.0
12		20.2	19.2	20.0	19.8	19.8	20.2	19.2	20.0	19.8	19.8
18		20.0	19.2	20.0	19.6	19.8	20.0	19.2	20.0	19.6	19.8

APPENDIX C

STOCKFEED AND HYDRAULIC LOADING RATES AS PERCENT OF INTENDED RATES

1. STOCKFEED AND HYDRAULIC LOADING RATES COMPUTATIONS
2. DAILY STOCKFEED RATES AS PERCENT OF INTENDED RATES
3. DAILY HYDRAULIC LOADING RATES COLUMN I AS PERCENT OF INTENDED RATES
4. DAILY HYDRAULIC LOADING RATES COLUMN II AS PERCENT OF INTENDED RATES
5. DAILY HYDRAULIC LOADING RATES COLUMN III AS PERCENT OF INTENDED RATES

STOCKFEED AND SUBSTRATE LOADING RATE COMPUTATIONS

The stockfeed rates were so adjusted that with proper column hydraulic rates a substrate strength of 0.2 gm/l of milksolids could be maintained. This strength is approximately 215 ppm COD.

In order to find the pounds of COD applied per acre per day for a column at a given day:

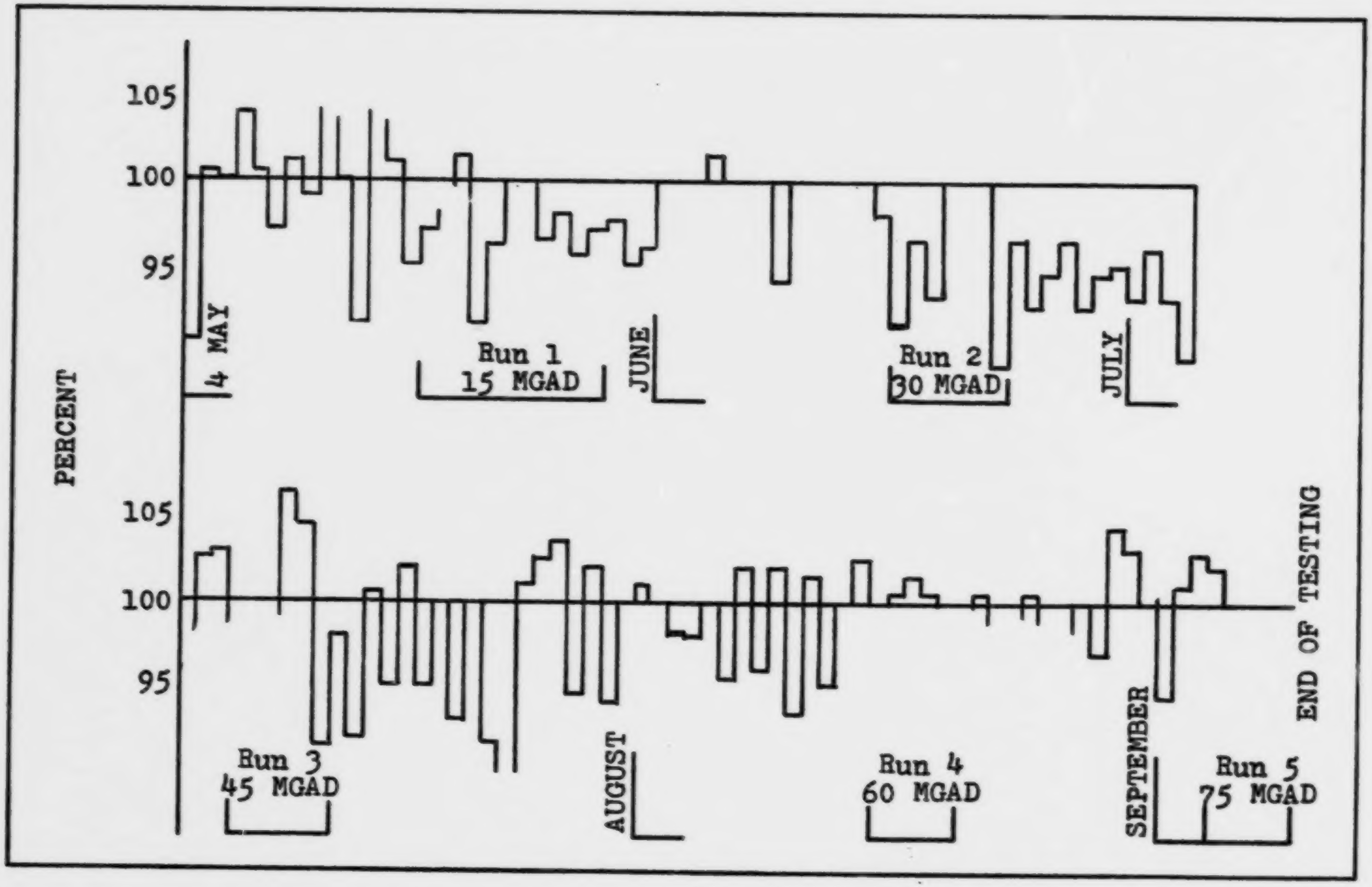
1. Obtain percentage rates for stockfeed rate (a) and column hydraulic rate (b).
2. Determine applicable rate in mgad (c).
3. Compute pounds of COD/acre/day.

$$(a\ \%)(b\ \%)(c\ \text{mgad})(8.34)\left(\frac{215}{10^6}\right)^{*} =$$

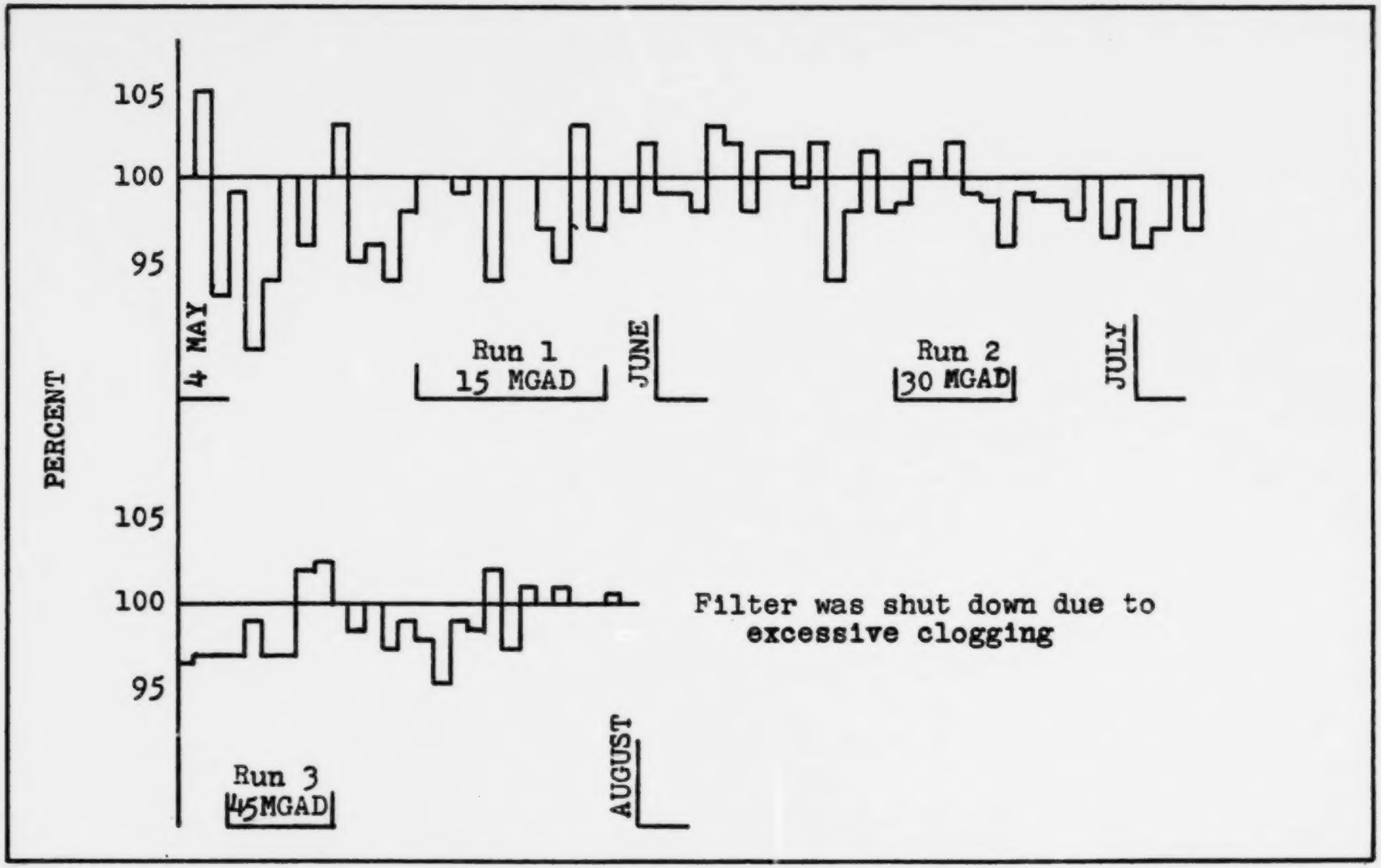
$$abc \times 1.168 \times 10^3\ \text{lbs COD/acre/day}$$

---

* COD quantity based on modified COD test without 1.55 factor

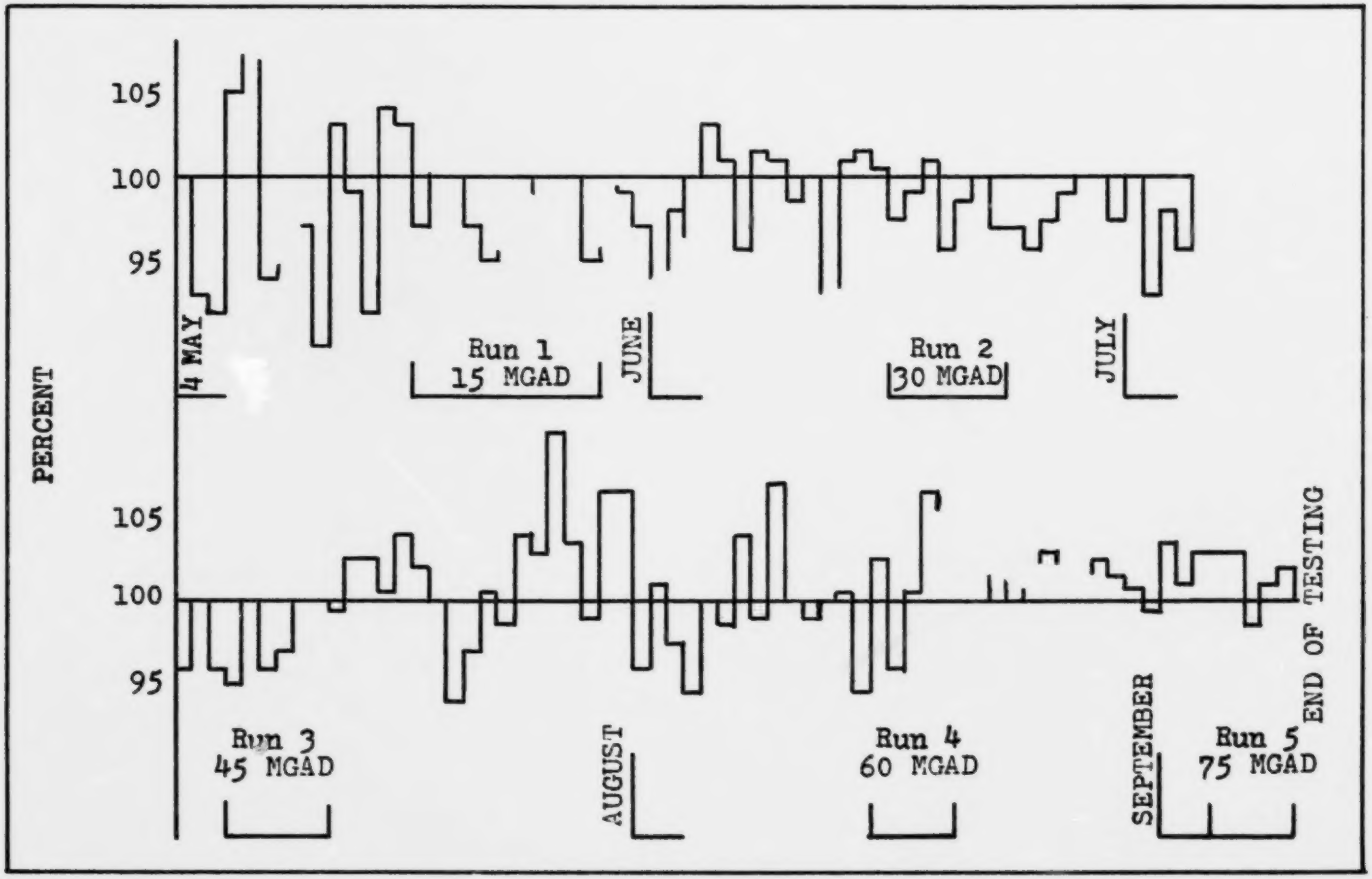


DAILY HYDRAULIC STOCKFEED LOADING RATES
AS
PERCENT OF INTENDED RATES

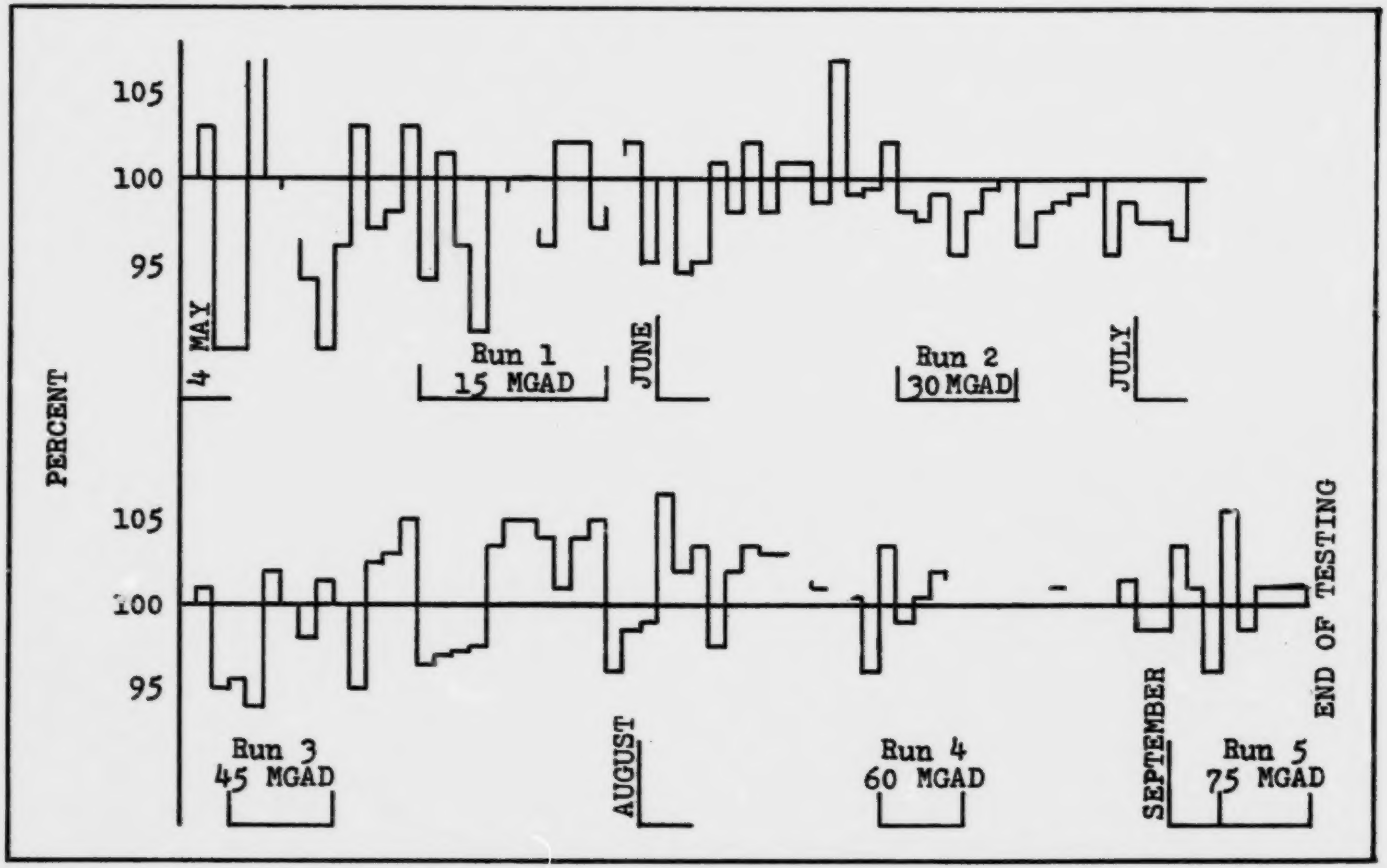


Filter was shut down due to excessive clogging

COLUMN I
DAILY HYDRAULIC LOADING RATES
AS
PERCENT OF INTENDED RATES



COLUMN II
DAILY HYDRAULIC LOADING RATES
AS
PERCENT OF INTENDED RATES



COLUMN III
DAILY HYDRAULIC LOADING RATES
AS
PERCENT OF INTENDED RATES

CONTACT TIME AND REACTION RATES FOR TRICKLING FILTERS

by

MICHAEL DAN ROACH

A THESIS

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degree of

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APPROVED:

Associate Professor of Civil Engineering

In Charge of Major

Head of Department of Civil Engineering

Dean of Graduate School

Date thesis is presented ____________________

Typed by Kathleen Lewis

AN ABSTRACT OF THE THESIS

Michael Dan Roach for the Master of Science in Civil Engineering
(Name) (Degree) (Major)

Date thesis is presented ____________________

Title Contact Time and Reaction Rates for Trickling Filters

Abstract approved ____
(Major Professor)

Three deep experimental filters were used to evaluate the influence of the physical factors of media size, depth of filter, and organic and hydraulic loading on contact time and the rate of removal of organic material by the biological growth on the filters. A further correlation was made between contact time and the COD removal rates.

The experimental filters were three columns, 5.8 inches in diameter and 18 feet in depth. Each column was packed with a constant size, smooth, spherical media. The media used were 9/16-, 7/8-, and 1-1/4-inch diameter marbles.

Tracer studies for contact time were made on the columns at 2-, 4-, 8-, and 16-foot levels and at hydraulic loadings ranging from 15-90 mgad. Sodium chloride was used as the tracer material. Contact time was determined for the three sizes of media without biota and for the 7/8-, and 1-1/4-inch diameter media with biota. Samples of the substrate were taken at the various levels and flow rates for COD determination for the tests run on the media with biota.

A step-wise regression analysis was performed on the data with the use of an IBM computer. Two empirical relationships were established

for contact time, one for the media without biota and the other for media with biota. A further empirical relationship correlated the COD remaining with the contact time.

The results of this analysis showed that contact time on the media without biota is inversely proportional to the 0.76 power of the hydraulic loading, inversely proportional to the 0.50 power of the diameter of the media, and directly proportional to 1.08 power of the filter depth. Contact time on media with biota is inversely proportional to the 1.05 power of the hydraulic loading, and directly proportional to the 1.44 power of the filter depth.

The third empirical equation established a relationship for COD remaining as a function of time, where the fraction of COD remaining is inversely proportional to the 0.19 power of the contact time.

TABLE OF CONTENTS

- INTRODUCTION 1
- PURPOSE 2
- SCOPE 2
- METHOD OF STUDY 3
- THEORY OF FILTRATION 4
  - General Description of Filter 4
  - Organic Removal 5
  - Oxygen Transfer 7
  - Temperature 8
  - Contact Time and Reaction Rates 8
- EXPERIMENTAL EQUIPMENT AND METHODS 11
  - Physical Design 11
    - Equipment 11
    - Media 14
    - Application Rates and Distribution 14
    - Substrate 15
  - Operating Procedure 16
  - Experimental Methods 18
    - Tracer 18
    - Sample Collection and COD Tests 21
- ANALYSIS OF DATA 23
  - Determination of Median Residence Time 23
  - Equation of Contact Time 23
  - Equation of COD Removal 26
- DISCUSSION OF DATA 27
  - Influence of Clean Media on Contact Time 27
    - Experimental Results 27
      - General 27
      - Media 27
      - Hydraulic Loading 28
      - Depth 32
    - Empirical Equation and Experimental Results 32
  - Influence of Biological Growth on Contact Time 37
    - Experimental Results 37
      - General 37
      - Growth 38

TABLE OF CONTENTS (CONTINUED)

Hydraulic Loading 41
Depth 44
Media 47
Empirical Equation and Experimental Results 47
Effect of Contact Time on COD Removal Rates 49
Experimental Results 49
Empirical Equation for COD Removal 52

SUMMARY 54

CONCLUSIONS 56

LIST OF TABLES

Table Page

1. Analysis of Filter Media 14

2. Analysis of Milk Solids 15

3. Summary of Statistical Analysis for Contact Time on Media Without Growth 24

4. Summary of Statistical Analysis for Contact Time on Media With Growth 25

LIST OF FIGURES

Figure Page

1. Experimental deep trickling filters - laboratory units . . . 12
2. Typical sample ports for filter units 12
3. Flow diagram - experimental filter units 13
4. Flow-through curve using NaCl tracer 20
5. Median time versus hydraulic loading for column I without biological growth 29
6. Median time versus hydraulic loading for column II without biological growth 30
7. Median time versus hydraulic loading for column III without biological growth 31
8. Median time versus depth for column I without biological growth 33
9. Median time versus depth for column II without biological growth 34
10. Median time versus depth for column III without biological growth 35
11. Comparison of empirical equation and experimental data for media without growth 36
12. Biological growth versus filter depth for column II 39
13. Biological growth versus filter depth for column III 40
14. Median time versus hydraulic loading for column II with biological growth 42
15. Median time versus hydraulic loading for column III with biological growth 43
16. Median time versus depth for column II with biological growth 45
17. Median time versus depth for column III with biological growth 46
18. Comparison of empirical equation and experimental data for media with growth 48

LIST OF FIGURES (CONTINUED)

Figure Page

19. Per cent COD remaining versus depth for column II 50

20. Per cent COD remaining versus depth for column III 51

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Michael D. Roach

CONTACT TIME AND REACTION RATES FOR TRICKLING FILTERS

INTRODUCTION

The trickling filter has been used as a means of biologically treating sewage for more than a half of a century. Much of the design has come from experience and trial and error application of previous knowledge. The determination of basic parameters from controlled laboratory models and pilot plants is relatively young. More recently there has been an attempt to develop mathematical models of the trickling filter.

In either experimental filters or mathematical models the trickling filter may be divided into the physical system and the biological system. A large amount of the experimental laboratory work has been done on either one or the other of the two systems. Many of the small scale laboratory units have been used to define one parameter of either the physical or biological system. While full-scale operating filters may be used to study the biophysical system, they have the disadvantage of not being able to be operated under controlled conditions.

It would seem desirable to study the combined biophysical system of the filter under controlled conditions, correlating the physical factors of media size, depth of filter, and organic and hydraulic loading rates with the biological activity of the filter slime. A controlled study of this nature should give a better knowledge of the mechanisms and performance of a trickling filter.

The degree of purification or removal of organic material from any substrate is dependent on the chance that the microbial population has to be in contact with the substrate. This time of contact is the time that it takes one particle of fluid to pass through the filter.

The rate of removal of organic material by the filter is essentially a function of the concentration of the organic material, the active biota, the temperature, and the time of retention of the substrate in the filter. Since the rate of removal and the degree of purification are largely dependent on contact time, the correlation of contact time with the rate of removal, while holding the other parameters of media size, temperature, hydraulic and organic loading constant, should give a reliable indication of the overall organic removal or performance that may be expected of a trickling filter.

PURPOSE

The purpose of this thesis is to correlate removal rates of organic material in the laboratory model of a trickling filter with the time of retention of liquid in the filter. The study attempts to provide more basic understanding of the performance of trickling filters and to determine if experimental evidence under controlled conditions will approximate or substantiate previous theoretical derivations.

SCOPE

The scope of this study consists of the determination of contact time and COD removal as a function of flow rate and media size. Initially, contact time will be found on a filter of clean media and a later correction applied for this same media with microbial growth.

Once the relationship has been established for contact time for a certain size media with growth, a further correlation will be made between COD removal and contact time. This last expression can then be stated in terms of design parameters for the expected COD removal through a filter bed of fixed media size and specified hydraulic loading of sewage or similar liquid waste.

METHOD OF STUDY

To determine contact time a series of tests were run on three sizes of media. The tests for contact time were divided into two phases. The first phase consisted of three data runs for contact time at different flow rates on media without biota. The second phase of tests consisted of three data runs for contact time at different flow rates on two sizes of media with biota.

Each run for both phases consisted of determining the contact time through 2-, 4-, 8-, and 16-foot sections of the filter column. The time of retention was determined by using NaCl as a tracer.

During the second phase of tests, samples for each run were taken from the influent, 2-, 4-, 8-, and 16-foot levels of the filter column and analyzed for temperature, pH, and chemical-oxygen demand (COD). Filter slime samples were taken at each of the sampling levels for determination of weight of growth per unit of surface area.

THEORY OF FILTRATION

General Description of Filter

A trickling filter is esentially a vertical column filled with a loosely packed solid, generally rock. Sewage or other liquid waste is distributed onto the filter intermittently or continuously by a rotary distributor. The sewage trickles down over the filter media by gravity and finally passes through an underdrain system to a secondary settling tank. As the liquid waste flows through the filter it is contacted with biological films on the filter media. Organic (BOD) removal by the microorganisms is accomplished by adsorption of the organic material onto the microbial film.

Aerobic conditions are maintained by the flow of air through the filter. Oxygen from the air in the voids of the filter bed is adsorbed by the liquid and permits aerobic metabolism by the microorganisms.

Generally, trickling filters are classified as low-rate or high-rate filters depending on the hydraulic and organic loading. The design criteria of a low-rate filter is two to four million gallons per acre per day (mgad) with an organic loading of 10 - 20 pounds of five day BOD per 1000 cubic feet of filter stone. The high-rate filter is classed hydraulically at 10 - 40 mgad with an organic loading up to 90 pounds of five day BOD per 1000 cubic feet of filter volume. The depths of low-rate filters range from six to ten feet. The high-rate filter is generally six feet in depth.

Organic Removal

As the liquid waste moves over the filter media, the method of transfer of mass from the fluid to the filter slime has been postulated to occur by biosorption and coagulation from that portion of flow which passes rapidly through the filter and by progressive removal of soluble constituents from the portion of flow with increased residence time (4). Behen et al. (1) states that the original concept of removal and storage is credited to E.B. Phelps (4). Phelps arrived at his conclusions by observing that 75 - 80 per cent BOD reduction seemed to occur in 15 to 20 minutes residence of the waste in the filter while it took seven days for this same reduction in a BOD bottle with excess oxygen.

A mechanism for adsorption is given by McKinney (13). He states that as the liquid flows through the filter bed, the liquid actually flows over the top of the microbial layer rather than through this layer. If the organic concentration of the flowing liquid is greater than that of the bound water on the microbial surface, organic matter will be transferred from the flowing wastes to the bound-water layer. This concentration gradient concept suggests that the most rapid transfer will occur when the incoming organic concentration is high and the bound-water concentration is at a minimum. General observation of trickling filters supports this concept. The upper layers of the filter receive the highest concentration of organic matter which accounts for the observed greater microbial growth in the top portion of the filter than in the lower portion.

A second mechanism that has been suggested is that the removal of BOD from the waste is due to high rates of oxidation at the surface of the microbial film. This concept has been disputed since experiences with other types of microbial surfaces have not given comparable high rates of oxidation in like aerobic systems (1).

The removal of organic material by adsorption is a function of contact time, the organic concentration of the waste and the microbial surface present. Schulze (17) assumed that the treatment capacity of a filter was essentially determined by two main factors; (a) the amount of active film per unit of filter volume, and (b) the contact time between the waste and this film. The contact time depends on the microbial surface area and hydraulic load. The active film will depend on temperature, the surface area available and the supply of food and oxygen.

The microbial film is also a function of the media size and the depth of the filter. According to McKinney (13), the microbial mass of this film adheres to the media surface by Van der Waal forces of attraction for two surfaces. The microogranisms build one on top of the other. As the layers increase, the lower layers do not receive food or oxygen and these layers shift to an anaerobic endogenous metabolism. As the cells in the lower layers die and lyse, the surface responsible for holding the microbial mass is destroyed. The biota drops or "sloughs" from the media. Organic removal is a minimum when the growth drops from the media and increases to a maximum when the media is covered with a thin layer of microorganisms.

Oxygen Transfer

Oxygen transfer plays an important role in filter performance along with retention time and the quantity of filter film. According to Eckenfelder (4), oxygen is transferred to the film from the waste liquid passing through the filter. McKinney (13) states that the oxygen is transferred from the void spaces due to the driving force of an oxygen deficit existing in the liquid at the air-liquid interface. In either case the rate of transfer is related to the oxygen deficit and liquid characteristics and may be related by:

$$\frac{dc}{dt} = K(C_s - C) \qquad \text{Eq. 1}$$

Where:

C = actual oxygen present
C_s = oxygen saturation value
K = constant for liquid characteristics

The Water Pollution Research Board (7) related the rate of oxygen transfer to the saturation deficit, hydraulic loading, depth and physical characteristic of the filter as:

$$\frac{dc}{dD} = \frac{K'}{Q^{0.5}} (Cs - C) \qquad \text{Eq. 2}$$

Where:

D = filter depth
Q = hydraulic loading per unit filter surface
K' = modified rate coefficient

The quantity of active film will depend on the depth to which oxygen can penetrate to maintain aerobic conditions. Research by

Shulze (17) indicates that the maximum aerobic depth is two to three mm.

Temperature

Temperature has an influence on filter performance in that the metabolic activity of the microbial population increases with temperature. This microbial metabolism is a function of the liquid temperature and not of the air temperature (16). Howland (9) has shown the effect of temperature on filter performance by the relationship:

$$E = E_{20}\ 1.035^{(T-20)} \qquad \text{Eq. 3}$$

Where:

E_{20} = BOD removal efficiency at 20°C
E = BOD removal efficiency
T = temperature, in °C

Contact Time and Reaction Rates

The degree of purification or organic removal is dependent upon the contact time between the waste and the microbial population of the filter. The residence time of a liquid in turn is dependent upon hydraulic load and the filter surface area. In determining some relationship for the removal of organic material (BOD), Eckenfelder (5) proposed the following approach. He assumes a first order kinetic reaction to relate contact time with organic removal by the same type of equation proposed by Howland (10), and Shulze (18). The variables may be related by:

$$\frac{Le}{Lo} = e^{-kt} \qquad \text{Eq. 4}$$

Where:

Le = BOD remaining in the filter effluent
Lo = BOD applied to the filter
K = coefficient incorporating the surface area of active film per unit volume

The contact time "t" can be described by the relationship: (17) (10) (20) (2).

$$t = CD/Q^n \qquad \text{Eq. 5}$$

Where:

t = contact time
D = filter depth
Q = hydraulic loading

The constant C, and the exponent n will vary with the type of filter media and hydraulic characteristics of the system.

Eckenfelder (5) further shows that the surface area of the film varies with type and distribution of the filter media and the filter depth, and can be mathematically approximated by:

$$C \sim 1/D^m \qquad \text{Eq. 6}$$

in which C is related to the mean active filter film per unit volume throughout the filter depth.

Modification of Equation (4) by Eckenfelder, (5) with Equations (5) and (6) gives:

$$\frac{Le}{Lo} = e^{(-KD^{1-m})/Q^n} \qquad \text{Eq. 7}$$

which presumes all the components of organic waste are removed at the same rate. But evidence shows that BOD removal for sewage decreases with concentration or time (1) (18). To account for this decrease in removal Eckenfelder (5) modified Equation (7) with a retardant form of the equation for overall removal:

$$\frac{Le}{Lo} = \frac{100}{1+\frac{CD^{(1-m)}}{Q^{n}}} \qquad \text{Eq. 8}$$

Determination of the constant C and the exponents (1-m) and n from the various studies yields an equation for the design of rock filters using domestic sewage where:

$$\frac{Le}{Lo} = \frac{100}{1+\frac{(2.5)D^{0.67}}{Q^{0.50}}} \qquad \text{Eq. 9}$$

Other equations for contact time have been formulated by various authors in the literature. McDermott (11) found contact time on a 23-foot column of 3-1/2 inch balls to be:

$$t = 30.2\ D^{1.08}\ Q^{-0.55} \qquad \text{Eq. 10}$$

Sinkoff _et al._ (20) found residence time for glass spheres as:

$$t = 3.0\ D\ \frac{\nu^{1/2}}{g^{1/3}}\ \left(\frac{S}{Q}\right)^{0.83} \qquad \text{Eq. 11}$$

and for porcelain spheres as:

$$t = 1.5\ D\ \frac{\nu^{0.20}}{g^{1/3}}\ \left(\frac{S}{Q}\right)^{0.53} \qquad \text{Eq. 12}$$

Where:

ν = kinematic viscosity
g = gravitational constant
s = specific surface

The specific surface is defined as the surface area of the media divided by the volume occupied by this media. Howland (10) derived a theoretical equation for flow of a liquid over a sphere where:

$$t = 2.6\left(\frac{3\nu}{g}\right)^{1/3}\ \frac{2\pi^{2/3}\ \ \nu^{5/3}}{Q^{2/3}} \qquad \text{Eq. 13}$$

in which r = radius of the sphere.

EXPERIMENTAL EQUIPMENT AND METHODS

Physical Design

Equipment

Three laboratory deep trickling filters (Figure 1) were erected in the spring of 1962 by Seaders (19). Each filter was a 5.8 inch diameter column 18 feet in height. Each column was filled with a constant-size spherical media. Column I was packed with 9/16 inch diameter marbles. Column II was packed with 7/8 inch diameter marbles and Column III was packed with 1-1/4 inch diameter ceramic spheres. Each column had sampling ports at 1-, 2-, 3-, 4-, 6-, 8-, 10-, 12-, 14-, 16-, and 18-foot levels from the top of the filter. Sampling trays (Figure 2) were inserted in each port for collection of growth samples. Each sample tray contained 40, 15, and 8 marbles for Column I, Column II, and Column III respectively.

The influent feeding apparatus was constructed so the hydraulic loading and organic loading could be controlled to allow the filters to operate at varied flow rates. The flow pattern for feeding is shown in Figure 3. The feeding apparatus consisted of a refrigerated stock-feed tank which was fed into a constant level feed-mixing tank for each filter. A timer and solenoid valve determined operation of pneumatically operated positive displacement pumps which transferred the stock feed to the mixing tanks. Recirculation pumps provided continuous mixing of stock feed with the make up water (tap water)

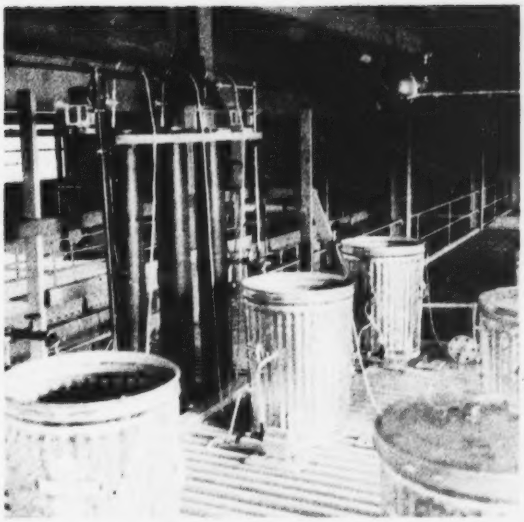

Figure 1. Experimental deep trickling filters-laboratory units.

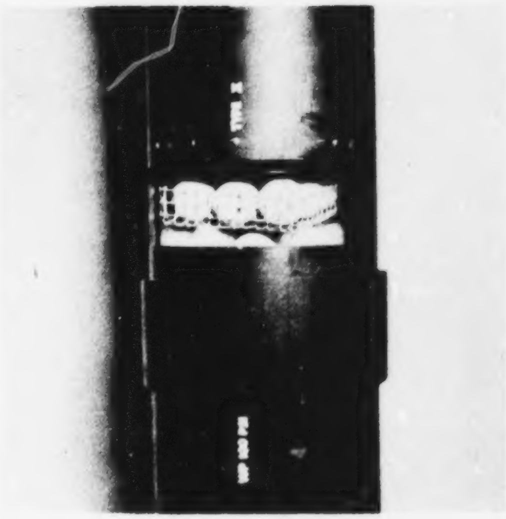

Figure 2. Typical sample ports for filter units.

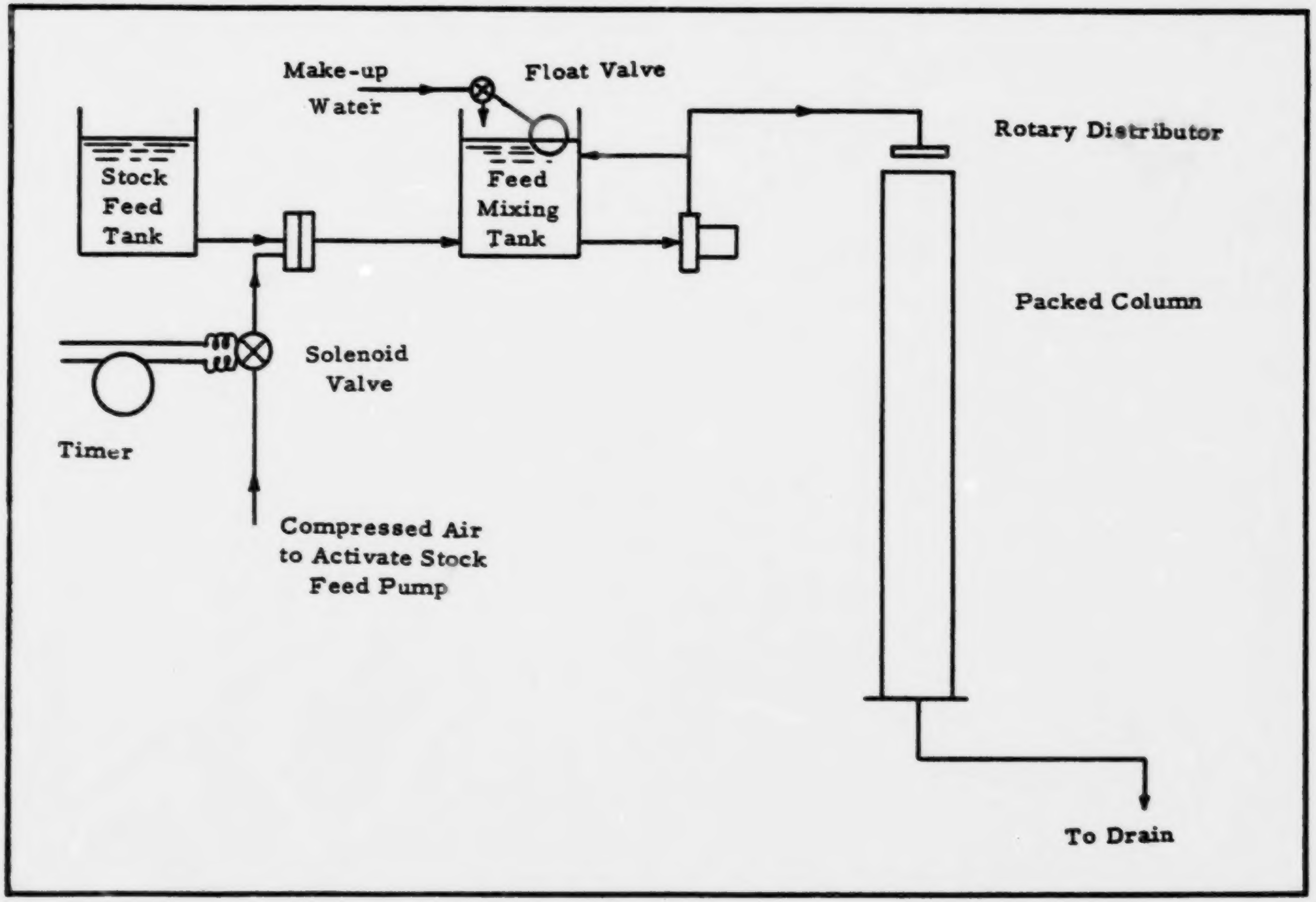
Make-up
Water
Float Valve
Rotary Distributor
Stock
Feed
Tank
Feed
Mixing
Tank
Packed Column
Solenoid
Valve
Timer
Compressed Air
to Activate Stock
Feed Pump
To Drain

Figure 3. Flow diagram - Experimental filter units

and pumped the resulting feed mixture to rotary distributors at the top of each filter column. A constant strength feed was maintained by proportioning the strength of the stock feed to the flow rate that was being applied to the filters. The flow rate to each filter column was controlled by means of a stopcock located just ahead of the rotary distributors.

Media

In design of the experimental filters it was desired that the media size be known. To meet this criteria glass marbles and ceramic spheres were chosen. The glass marbles were 9/16-inch and 7/8-inch in diameter respectively for Columns I and II. The ceramic spheres were 1-1/4 inch in diameter for Column III. The mean diameter and weight was determined for each size by Seaders (19). A summary of his analysis is shown below in Table 1.

TABLE 1

ANALYSIS OF FILTER MEDIA
Seaders (19)

Nominal size, inches	9/16	7/8	1-1/4
Mean diameter, mm	14.14	23.28	31.43
Mean wt./marble, gms	3.57	16.24	38.25

Application Rates and Distribution

The filters were designed to operate at 5 - 120 mgad. The flow rates were varied by use of stopcock valves ahead of the rotary distributor. The distributor for each filter was a belt driven four-inch diameter pulley with the feed line freely mounted on the rim. The distributor made one revolution every 30 seconds. It was felt that within a foot from the top of the bed that the flow would be evenly distributed. To minimize wall effects and short circuting, circular drip rings were installed at each sampling port to redistribute any wall flow.

Substrate

Dry milk solids were used to provide the organic load for the filters. Feed strength of 0.2 grams of milk solids per liter of tap water was used to give a BOD strength of 130 to 140 mg/l and a COD strength of 220 mg/l. The dry milk solids were analyzed by Seaders (19). The results of his analysis are shown in Table 2.

TABLE 2

ANALYSIS OF MILK SOLIDS
Seaders (19)

COD		1075	mg/gm
BOD		700-775	"
Nitrogen:	Organic - N	50	"
	Ammonia - NH_3	0	"
	Nitrite - NO_2	0	"
	Nitrate - NO_3	0	"
Phosphorous:	Phosphate - PO_4	29	"

Operating Procedure

The experimental stage of this study was divided into two phases. The first phase was concerned with determination of contact time at different flow rates on clean media. The second phase was concerned with determination of contact time at different hydraulic loading rates on media with microbial growth.

Initially only Column II and III were used in the test series since previous work (19) (15) had shown that the 9/16 inch diameter marbles of Column I were an unsuitable media because of the clogging and ponding associated with this filter for increased loading. Later, in the experimental study when time permitted, contact time tests were conducted on Column I for clean media.

The first phase was started the first week in June 1963, with preliminary testing of different tracers through the filter with the final selection of NaCl as the tracer material. On June 19, 1963 the first data runs were made for a hydraulic loading of 15 mgad. The rest of the data runs for flow rates of 15-, 30-, 45-, 60-, and 90-mgad were run and the first phase was completed on July 2, 1963. Flow rates were checked and adjusted at the beginning of each run and at varying intervals thereafter.

The second phase of the tests was initiated the first week of July, 1963, with seeding of the filter with raw sewage from the Corvallis Sewage Treatment Plant. The milk substrate was introduced to provide food for the microorganisms. Within a week after seeding the flow rate was set at 90 mgad and the filter allowed to establish growths at this rate. Growths were soon in evidence hanging in finger-like projections from the bottom of the screen used to support the media in each section. The high flow rate (90 mgad) was initiated in hope that the scouring action of the higher flow rates would reduce the build up of layers of inactive growth associated with clogging and ponding encountered by Seaders (19) at the lower flow rates. This hope was realized as no ponding or clogging occurred during the testing period at the lower rates. Subsequent check tests, run later in the fall and starting at the lower rates of flow and proceeding to the higher rates of flow, were troubled considerably with clogging and ponding.

Tracer tests were started on July 23, 1963, at 90 mgad for media with microbial growth. At the end of the tests for each flow rate a new flow rate was set and two weeks allowed for the filter to establish equilibrium conditions at this new rate. Tests at 15 mgad (the final flow rate) for media with growth, were completed on September 19, 1963. Filter flys and red tubiflux worms were noticed the third week in August and appeared to be distributed throughout both columns. The Psychoda larve cleaned the fingerlike growths from screens in each sample port. The adult filter flys became a definite nuisance during sampling. To reduce this nuisance the outside of the columns were sprayed with DDT. The filter flys were still present at the end of the tests.

For each flow rate samplings were made at the 2-, 4-, 8-, and

16-foot levels for each run. These samples were analyzed for COD, pH and temperature. Growth samples were also obtained at corresponding levels for each flow rate.

A check run on contact time determinations for media with growth was made for each flow rate starting October 11, 1963, and ending December 6, 1963. The same procedure was used for these determination as was used for the initial tests except that only one data run was made for each flow rate and the order of the flow rates was reversed going from 15 mgad to 90 mgad.

Final tracer tests were made on Column I, with clean 9/16 inch diameter media, during the spring of 1964. The filters were dismantled the third week of June, 1964.

Experimental Methods

Tracer

To find the residence time of the liquid in the filter different tracers were considered. The criteria for a suitable tracer were that it exhibit the same hydraulic characteristics as the fluid and that it not be harmful or inhibit the microbial growth of the filter. Further requirements were that the tracer be dosed to the filter in small amounts so the flow would not be changed. The tracer also had to be economical and capable of being traced with the equipment available.

Three tracer materials were investigated. These were phosphate, methylene-blue dye and sodium chloride. Preliminary tests with phosphate showed that the samples (50 ml) needed for analysis by the colormetric Stannous Chloride method (23) required too long a period of collection at the low flow rates. The methylene-blue tracer analyzed by colormetric methods was rejected because the dye adhered to the media causing the apparent time of contact to be greater than actual.

Sodium chloride was selected as the tracer to be used when preliminary tests showed it met the criteria. Evaluation of the tracer was accomplished by conductance measurements with a Serfass Conductance Bridge. A 10 per cent stock NaCl solution gave a good range of conductance values when applied at the rate of one ml per foot of depth of the column.

A series of tracer tests were set up to measure the fluids residence time in 2-, 4-, 8-, and 16-foot sections of the filter column. At these column depths three data runs were made for each of the varied flow rates. To the top of a column an amount of tracer corresponding to one ml per foot of filter depth to be sampled was applied. The frequency of sampling varied according to media size, depth of column and flow rate. A ten ml sample was taken for each time interval. The samples were checked for conductance within 10-15 minutes of sampling. The conductance readings were plotted with time, (Figure 4) and the median residence time determined. The median time is defined as the time at which half the recovered tracer has emerged.

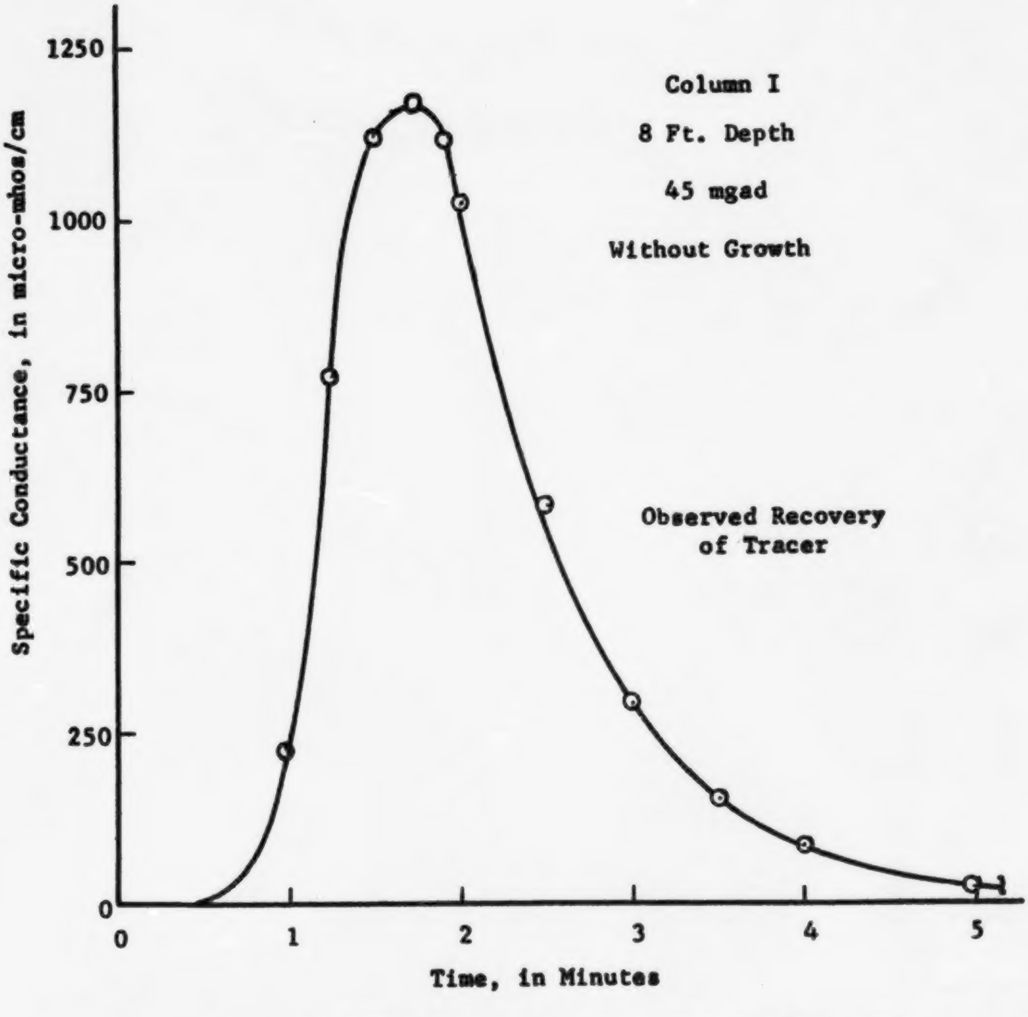

Figure 4. Flow - through curve using NaCl tracer.

Work in Britian (8) has shown that for radioactive tracer studies on trickling filters the percentage of tracer recovered versus time curve can be plotted as a straight line on logrithmic probability paper and the median time taken as the time at the 50 per cent level of recovered tracer.

Sample Collection and COD Tests

To determine organic removal and growth data, samples were taken on the media with growth at the influent, 2-, 4-, 8-, and 16-foot levels. The samples for substrate analysis consisted of three samples for each depth and flow rate which were taken to coincide with the three data runs of the tracer study. These samples were analyzed for COD, pH, and temperature. Growth samples were obtained by removing a prescribed number of marbles from the port of each sampling depth.

Growth analysis consisted of removing the growth from each marble by washing with distilled water. The water was evaporated and the growth dried in an oven at 103°C. The growth was then weighed. The prescribed number of marbles, (15 and 8 for Columns II and III respectively) represented a unit of surface area of approximately 250 cm^2.

The standard COD test (23) was modified by reducing the dichromate strength from 0.25 N to 0.1 N, and the sample size was increased from 50 ml to 100 ml. The titrant $[Fe(NH_4)_2SO_4]$ was reduced from 0.25 N to 0.1 N also. A digestion time of one hour was used. Seaders (19) showed that no difference was observed for digestion time ranging from 1/2 hour to two hours. Chloride determinations (23) were made and found to be negligible for correction of COD values.

ANALYSIS OF DATA

Determination of Median Residence Time

In order to evaluate median residence time the value of time at which half the tracer had emerged was determined. This determination was accomplished by finding 50 per cent of the area under the concentration (conductance) versus time curve (Figure 4), which is the value of 50 per cent of the recovered tracer. The area was found by numerical integration where the ordinate values for the approximating trapezoids were successive conductance readings. The abscissa value was the time interval between these readings. The time value corresponding to 50 per cent of the area was recorded as the median residence time.

Equation of Contact Time

The evaluation of a relationship for contact time as a function of flow rate, depth of filter, and media size was determined from the data. A step-wise regression analysis was performed with the use of an IBM 1620 computer after initial plotting showed the data approximated a straight line on logarithmic coordinates. Preliminary investigation showed the equation followed the form:

$$t = K \frac{D^n}{Q^m d^p} \qquad \text{Eq. 14}$$

Where:

t = contact time, seconds
D = depth of filter, feet

Q = hydraulic loading rate, mgad
d = diameter of media, inches
m, n, p, = exponents

and K is a constant dependent on the characteristics of the system.

Two correlations for contact time were determined from the data. One equation was found for contact time on the media without biota and a second equation for the same media with biota. The equation for media without growth was:

$$t = 207 \frac{D^{1.08}}{Q^{0.76}\ d^{0.50}} \qquad \text{Eq. 15}$$

and the equation for media with growth was:

$$t = 1057 \frac{D^{1.44}}{Q^{1.05}\ d^{0.09}} \qquad \text{Eq. 16}$$

For the clean media a multiple correlation coefficient of 0.99 was found and a T ratio greater than the absolute value of 11 determined for all three variables. An investigation of the T ratio shows all three variables are significant. The T ratio is the value of the exponent divided by its standard error. The summary of these results is seen in Table 3.

TABLE 3

SUMMARY OF STATISTICAL ANALYSIS FOR CONTACT TIME ON MEDIA WITHOUT GROWTH

Variable	Exponent	Std. Error	T Ratio
Diameter	-.50024	.04417	-11.32526
Flow Rate	-.75742	.02373	-31.01829
Depth	1.08332	.01877	57.69761

The multiple correlation coefficient for media with biota was 0.98 for the three variables of depth, flow rate, and media size, where depth and flow rate alone had a correlation coefficient of 0.98. This same correlation value suggests that the diameter of the media does not influence contact time. A T ratio of -0.336 (Table 4) further suggests the diameter of the media is not significant. The T value is within the 95 per cent confidence interval for a test of the hypothesis that T = 0.

TABLE 4

SUMMARY OF STATISTICAL ANALYSIS FOR CONTACT TIME ON MEDIA WITH GROWTH

Variable	Exponent	Std. Error	T Ratio
Diameter	-0.08611	.25594	-.33645
Flow Rate	-1.04539	.07977	-13.10411
Depth	-1.43746	.05018	28.64384

Omitting the diameter, the equation for contact time for media with growth is then written as:

$$t = 1072 \frac{D^{1.44}}{Q^{1.05}} \qquad \text{Eq. 17}$$

where the value of K has changed from 1057 to 1072 and the coefficients, the standard errors, and the T ratios have changed slightly.

Equation for COD Removal

An initial analysis was made on the COD data on the assumption that removal would follow a first order reaction as given by Equation (4). This assumption proved erroneous as the data did not follow a straight line plot on semi-logrithmic coordinates. Further investigations showed that a plot of per cent COD remaining versus time did approximate a straight line on logarithmic coordinates. An assumption was made that there was no COD removal during the first second of contact which allowed a logrithmic transformation of the data using t = 1 instead of t = 0 at the time of influent COD loading. A step-wise regression analysis, in this case, a least squares with one independent variable, time, was performed with the IBM 1620 computer. The result of this analysis is an equation for COD removal as a function of time:

$$\frac{Pe}{Po} = 1.03t^{-0.19} \qquad \text{Eq. 18}$$

Where:

Pe = COD remaining
Po = COD applied
t = contact time, seconds

The analysis of the data gave a correlation coefficient of 0.91, a standard error of 0.013 and a T ratio of 14.887. To use Equation (18) a determination of time may be made from Equation (17) and then the expected COD removal calculated.

DISCUSSION OF DATA

Influence of Clean Media on Contact Time

Experimental Results

General. The mean values of the three data runs were compared to find how the variables of media size, hydraulic loading and depth influence the time of contact on smooth, clean, spherical media. Contact time as the dependent variable was plotted separately against depth and against flow rate for each of the columns. These plots gave a series of curves which were helpful in visualizing how the different parameters affect contact time.

It should be noted that other factors beside media size, flow rate, and depth have an influence on the contact time of a liquid through a filter. Temperature, viscosity and density of the fluid, and roughness of the media all affect liquid flow. For the series of tracer tests on clean media the temperature ranged between 19 - 23 °C. No appreciable difference in the experimental results was expected as the viscosity of the tap water would not vary significantly in this small temperature range. The tap water approximated the flow characteristics of a weak settled sewage. If a fluid of different density and viscosity such as some industrial waste were applied to the filter, contact time could change markedly.

Media. The influence of media size on contact time can be seen from Equation (15) where time varies inversely to the 0.5 power of the diameter of the media. From this it can be seen that contact time decreases as the media size increases because the smaller surface area and greater pore size between the packing offers less resistance to fluid flow. In this study the difference in surface roughness was minimized by using smooth glass marbles and smooth ceramic spheres.

Hydraulic Loading. One of the main variables determining contact time is the hydraulic loading. Plots of contact time versus hydraulic loading at various depths for the three media sizes are shown in Figures 5, 6, and 7. From the family of curves in these plots it is seen that contact time decreases with increased flow rate. These curves approximate a series of straight parallel lines on logrithmic coordinates where $n = 0.76$ as obtained from Equation (15). With an increase in flow rate the curves flatten out indicating the greatest affect on contact time at the lower flow rates. This increase may be assumed to occur from a greater holdup of the liquid around and between the media at the lower flow rates than at the higher rates which may produce a flushing action. The curves indicate that a flow rate may be reached where any further increase would have no influence on the contact time. At this point the physical capabilities of the filter limit the velocity of the fluid and the curve becomes horizontal. Conversely, as the flow rate is decreased the holdup of the liquid due to attractive forces between the liquid and media would predominate and the curves would become asymptotic to the zero flow axis.

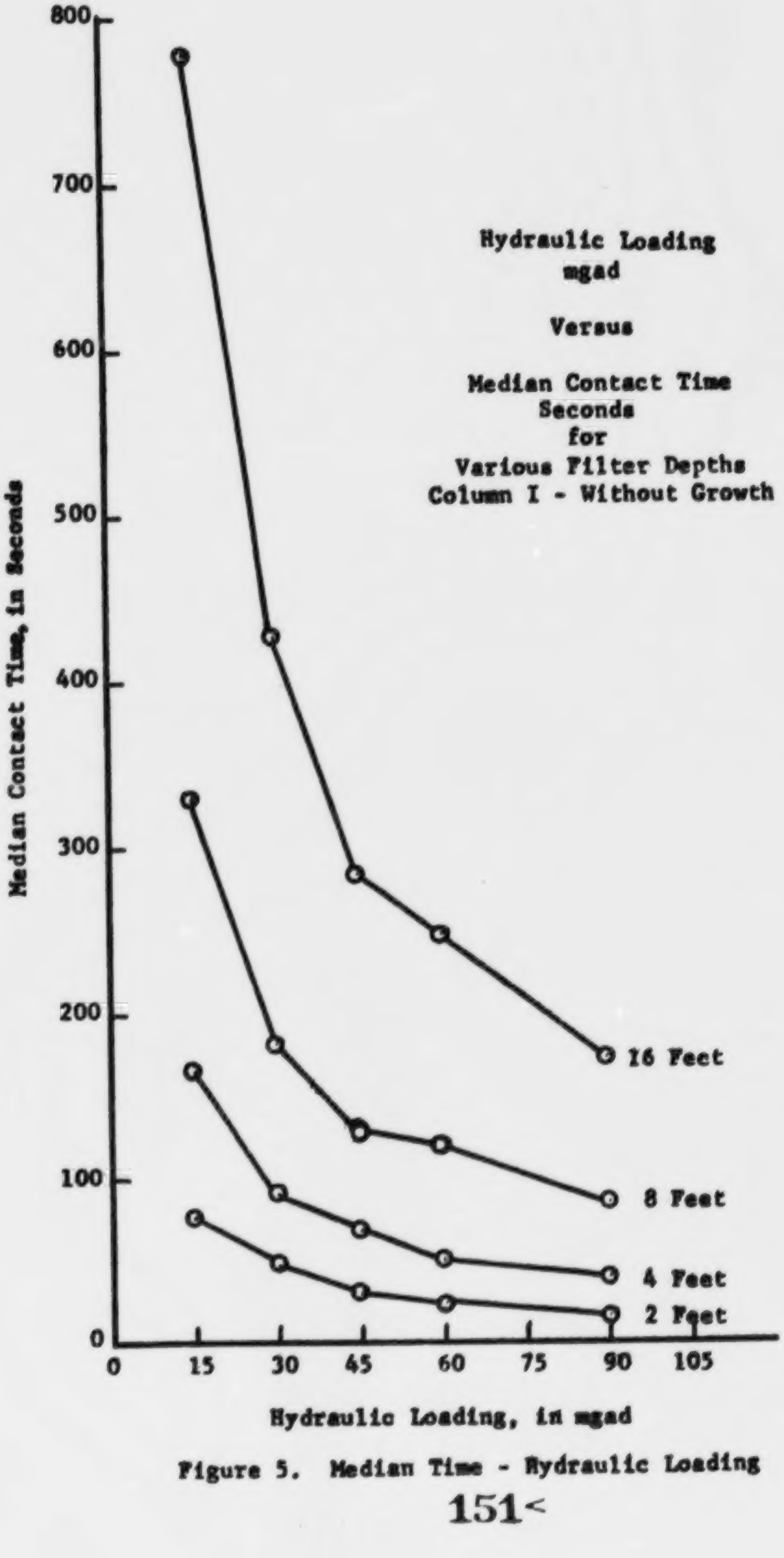

Figure 5. Median Time - Hydraulic Loading

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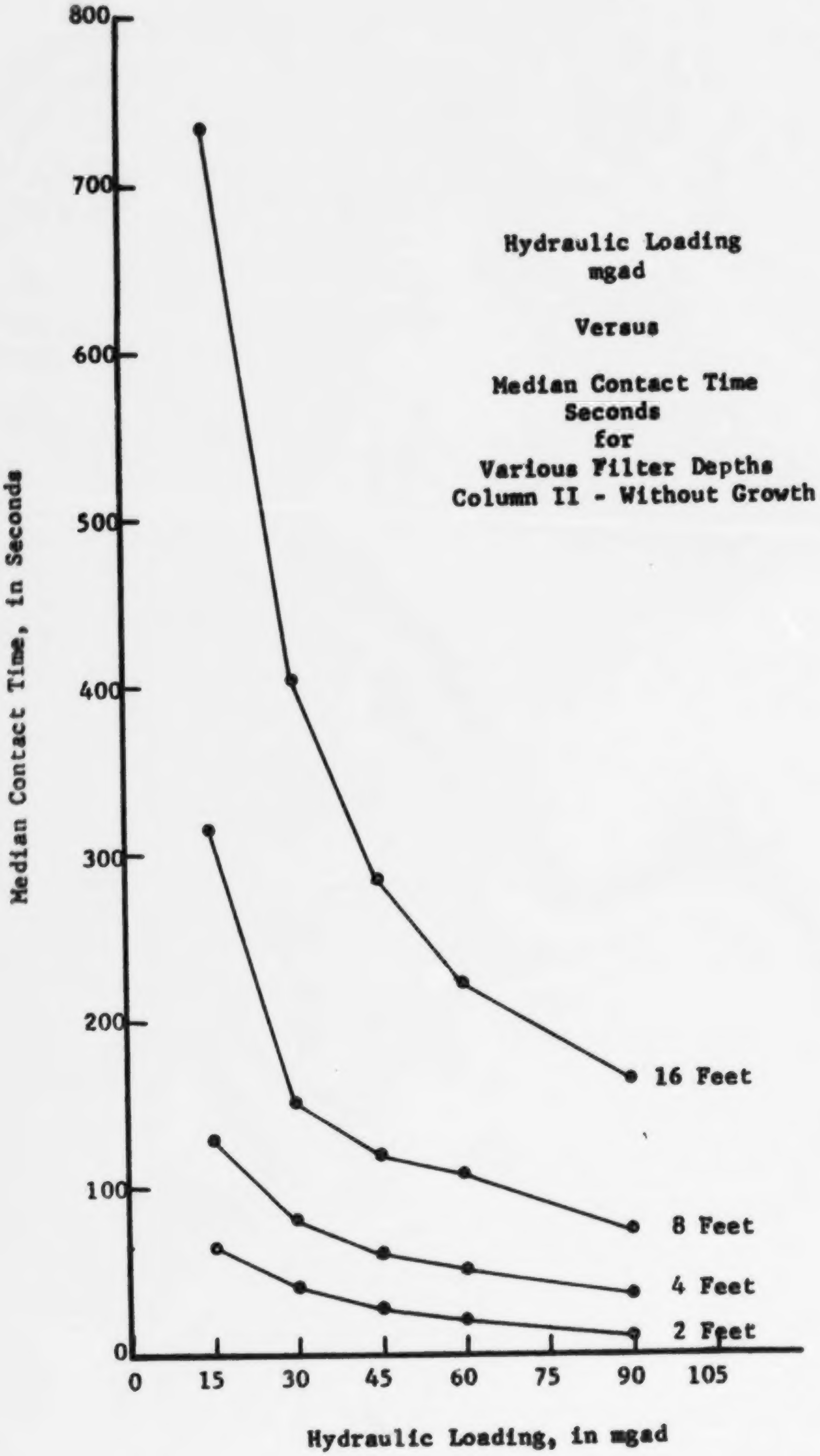

Figure 6. Median Time - Hydraulic Loading

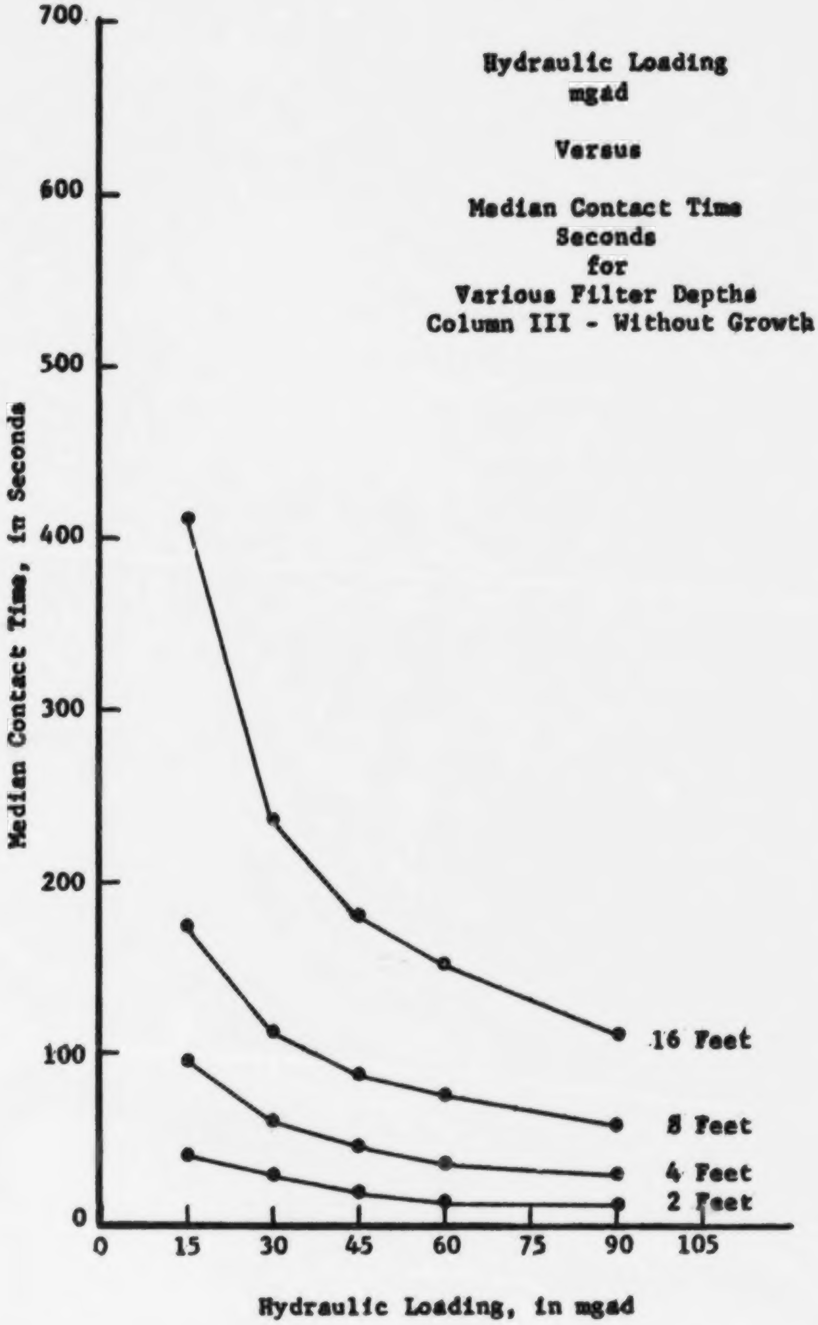

Figure 7. Median Time - Hydraulic Loading

The media size exerts a greater influence at the lower flow rates where the smaller media with the greater surface area provides a more tortuous path for the liquid to travel and greater holdup of the liquid is encountered. At the higher flow rates the effect of holdup is less and the influence of media size decreases.

Depth. Contact time varies with depth as shown in Figures 8, 9, and 10 for the three columns. The contact time increases at a greater rate for the lower flow rates producing a family of curves which approximate a series of parallel lines on logrithmic coordinates with $t \sim D^m$. From Equation (15), m is found to equal 1.08 indicating that contact time increases at a slightly greater rate than would be expected due just to an increase in the amount of media. For deep filters the increased contact time for unit of depth down the filter might be expected due to increased consolidation of the filter bed at lower depths. But for the experimental filters in this study, the media was supported at two-foot intervals and the degree of consolidation should not have been significantly different at any depth. The value of m greater than one then must be considered as characteristic of the system. The value of m equal to 1.08 is the same as that found by McDermott (11) on 3-1/2 inch rubber balls.

Empirical Equation and Experimental Results

A comparison of the experimental data and the solution of Equation (15) is shown in Figure 11. The smooth curves are the solution of Equation (15) for the indicated columns and depths.

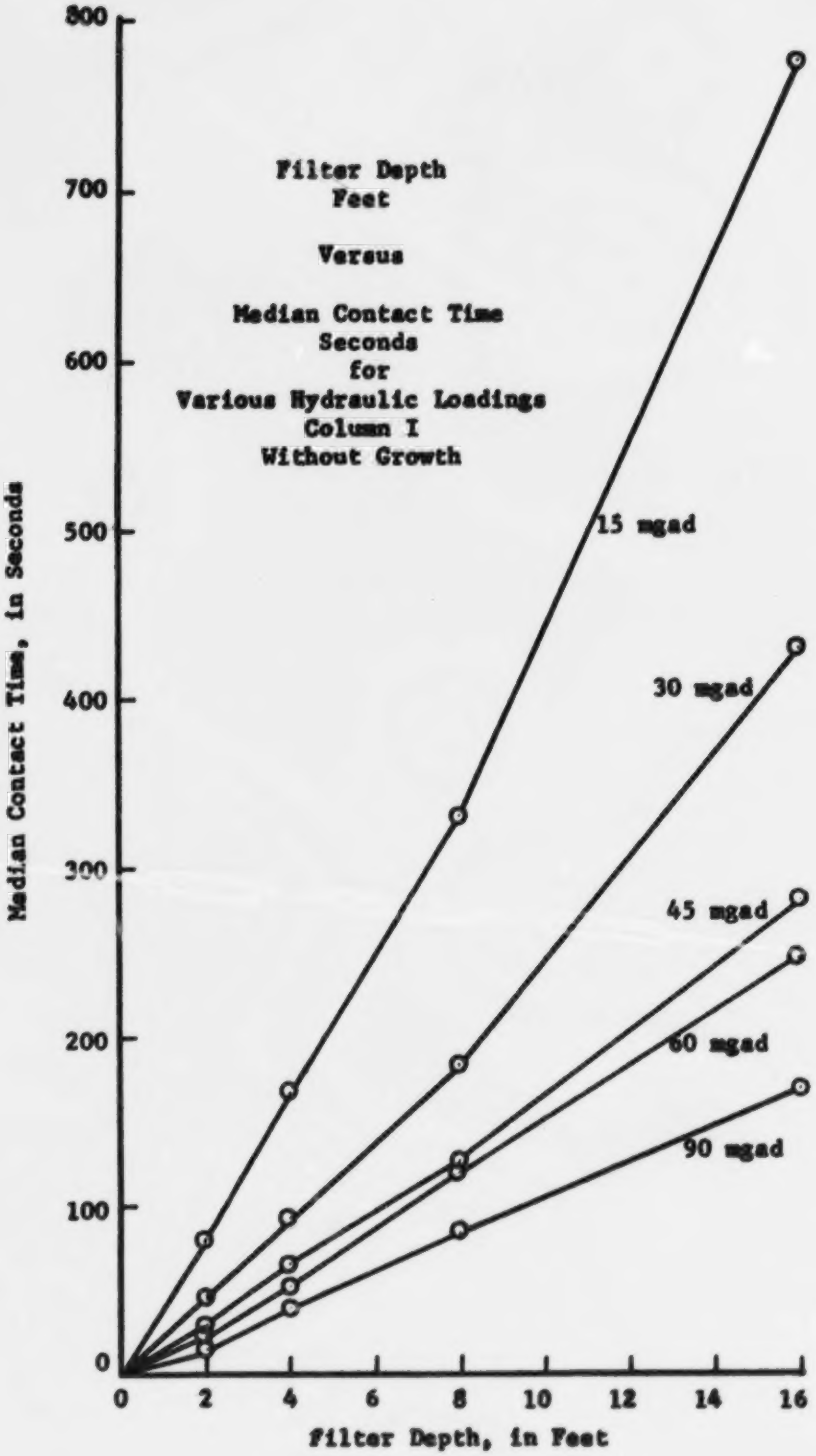

Figure 8. Median Time - Depth

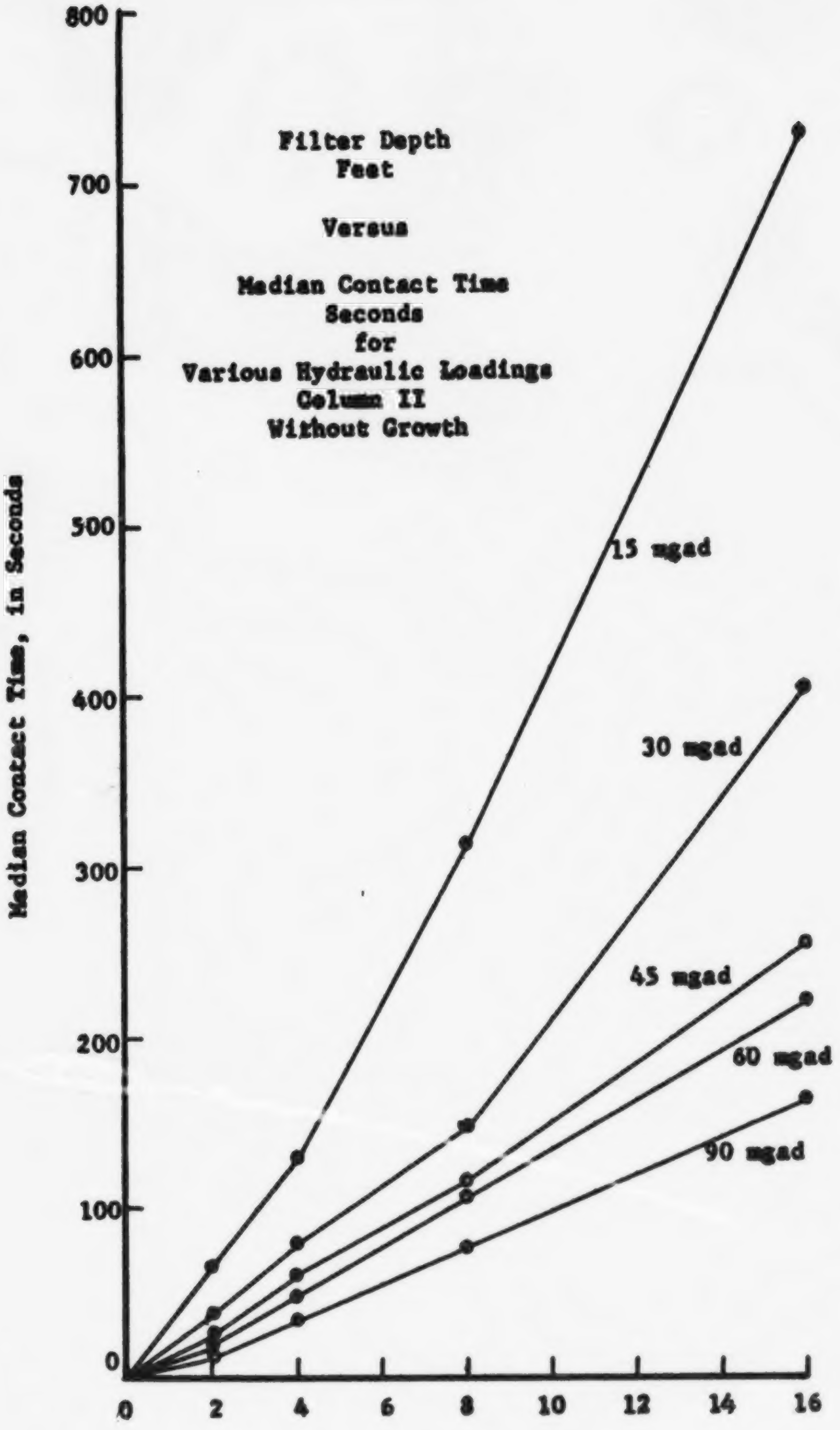

Figure 9. Median Time - Depth

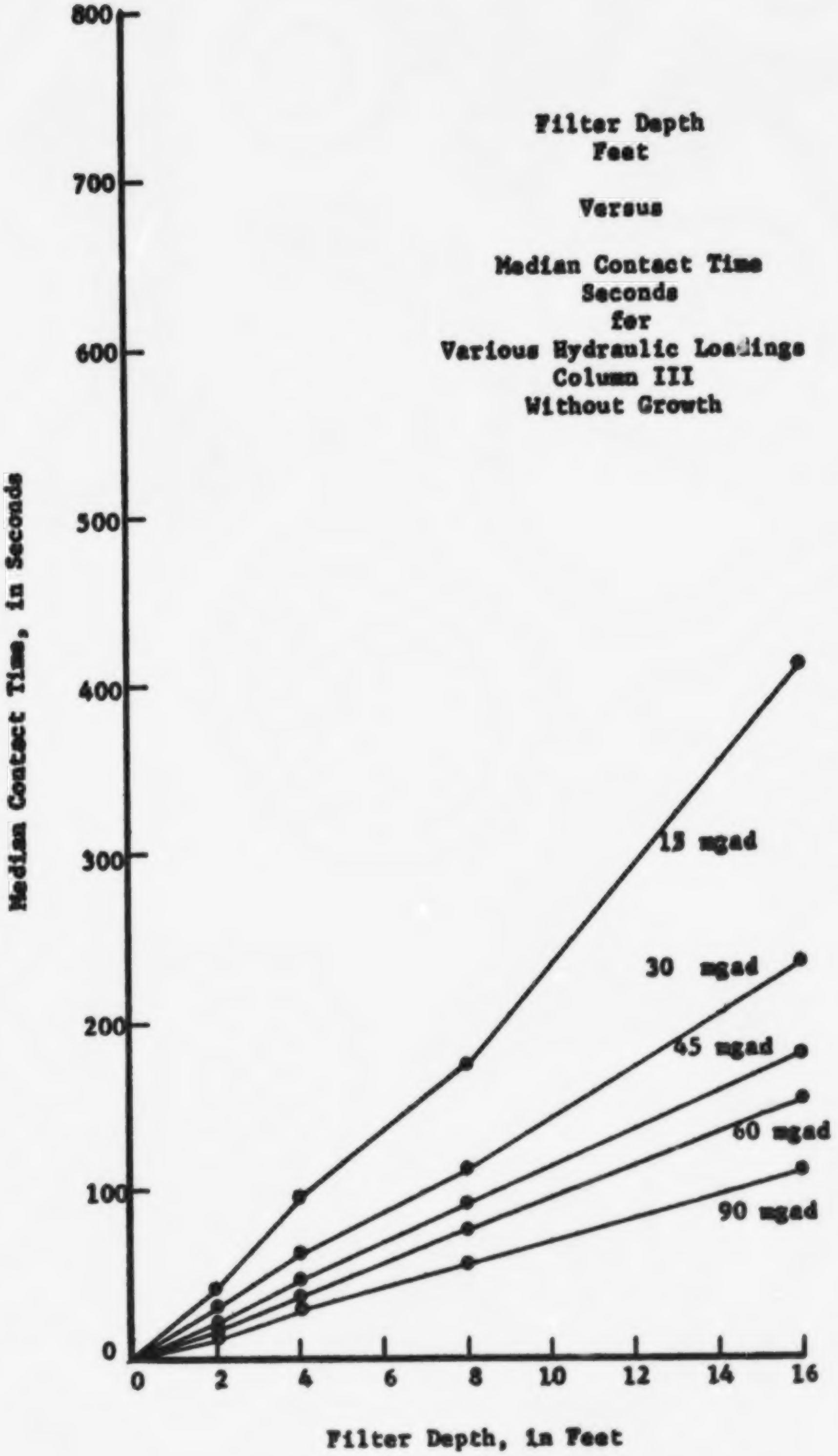

Figure 10. Median Time - Depth

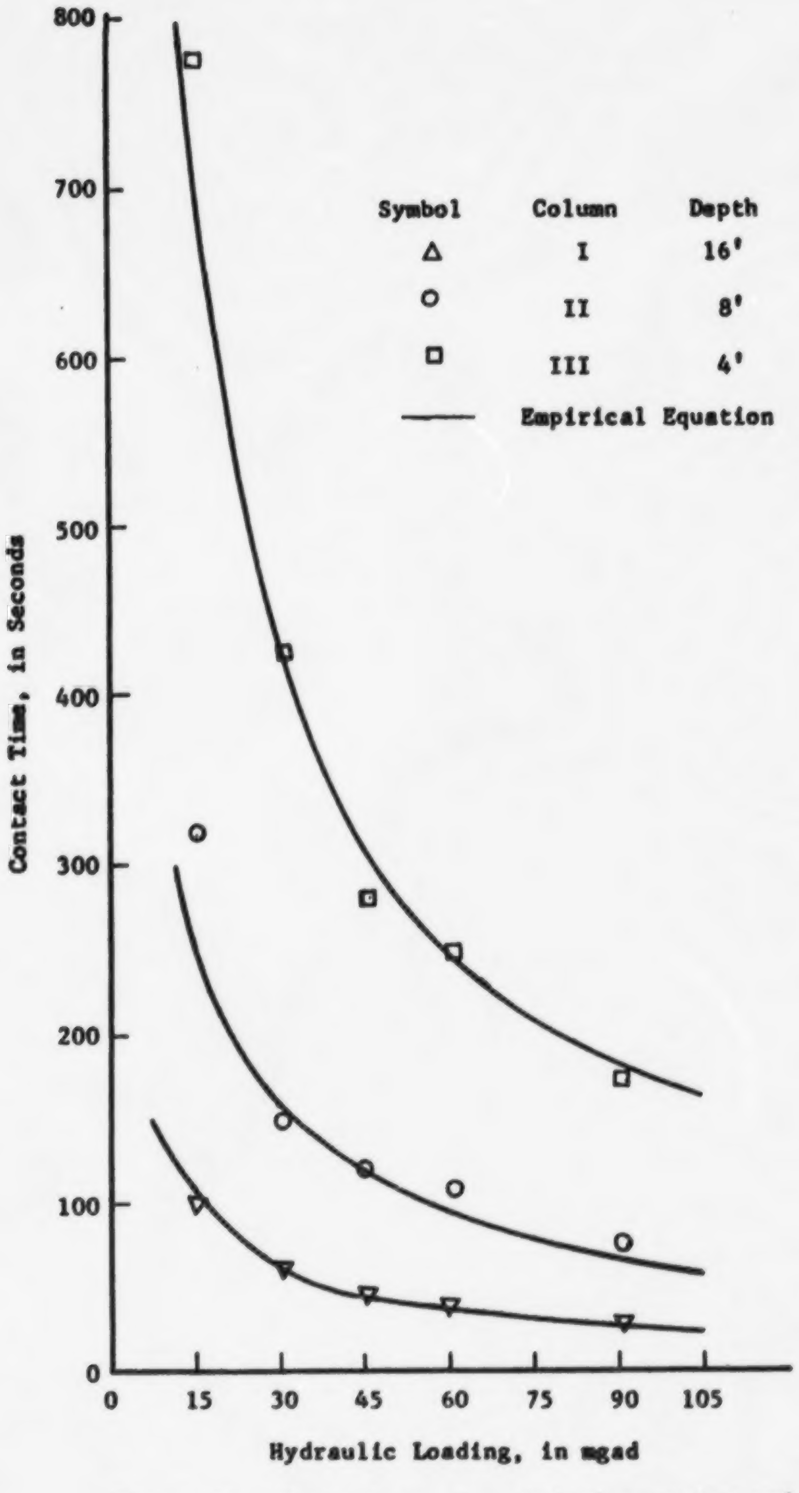

Figure 11. Comparison of empirical equation and experimental data for media without growth.

The plotted points are actual data points found in the experiment. The different depths and columns were chosen to obtain a large range of data values. The majority of data points lie close to the theoretical curve with a greater deviation at the low flow rates and corresponding greater contact time than at the higher flow rates.

Equation (15) is an empirical relationship with defined units. The application of the equation has been limited to describe the action of different variables on a clean media where conditions could be controlled. The form of the equation served as a guide to develop a relationship for contact time on the filter when growths are introduced.

Influence of Biological Growth on Contact Time

Experimental Results

General. Contact time studies were performed on Columns II and III for the filters with biological growth. Column I was not used since previous work (15)(19) showed that operation of the filter with biological growth was difficult due to ponding and clogging associated with the small media. The mean of three data runs were plotted and analyzed the same as the data for contact time on clean media. Equation (16) follows the same form as Equation (15), but the constant K, and the exponents are changed.

Due to biological growth on the media and in the voids of the bed, the contact time was increased from that for clean media. Maintenance of a uniform biological growth was difficult in that the growth will not only vary from filter to filter, but from day to day in the same filter. To provide some uniformity in formulating the equation, seven data points for median time were rejected on the basis that the stripping action of filter flies onthe growth allowed less contact time than would have been encountered under the normally observed growth conditions. These data points were recoginzed from plots of the data both on arithmetic and logrithmic coordinates.

The other factors beside filter flies that may have affected the biological growth of the filter were temperature and organic loading. The range of temperature for the data runs on the filter with growth was between 20-25 °C. Maintaining the temperature and organic feed fairly constant, the controlling factors both on the biological growth and contact time should be the same variables as for clean media, that is, depth, flow rate, and size of the media.

Growth. Growth samples were taken at each depth for each flow rate. Figures 12 and 13 show the results of this analysis for Columns II and III respectively. There is no general pattern to be determined from the growth analysis, but some observations can be made. At the 90 mgad flow rate the growth appears greater than at other flow rates contradicting the idea that scouring due to the high flow rate would reduce the growth below that found at lower flow rates. Possibly, the greater total organic load available at this rate produced the greater growth. Further examination shows that the growth appears to be heaviest at the 16 foot level in Column II. The

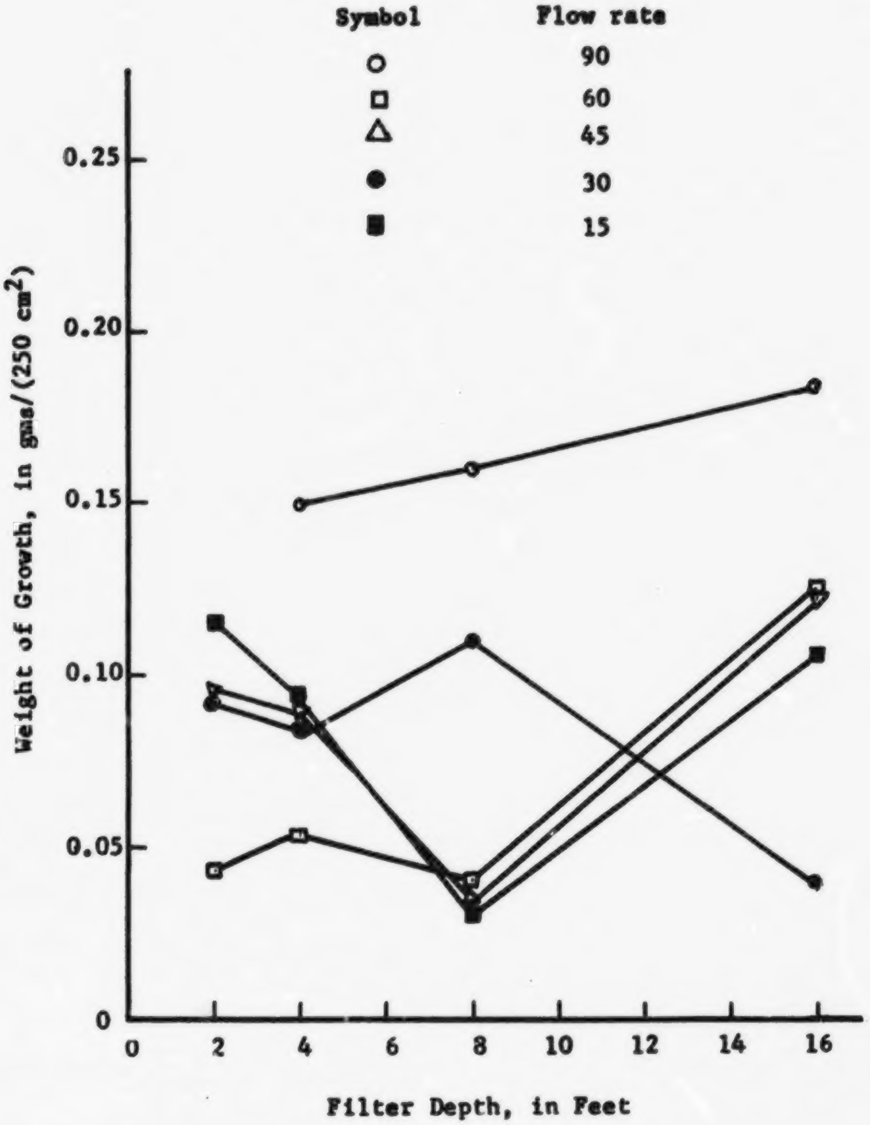

Figure 12. Biological growth versus filter depth for Column II

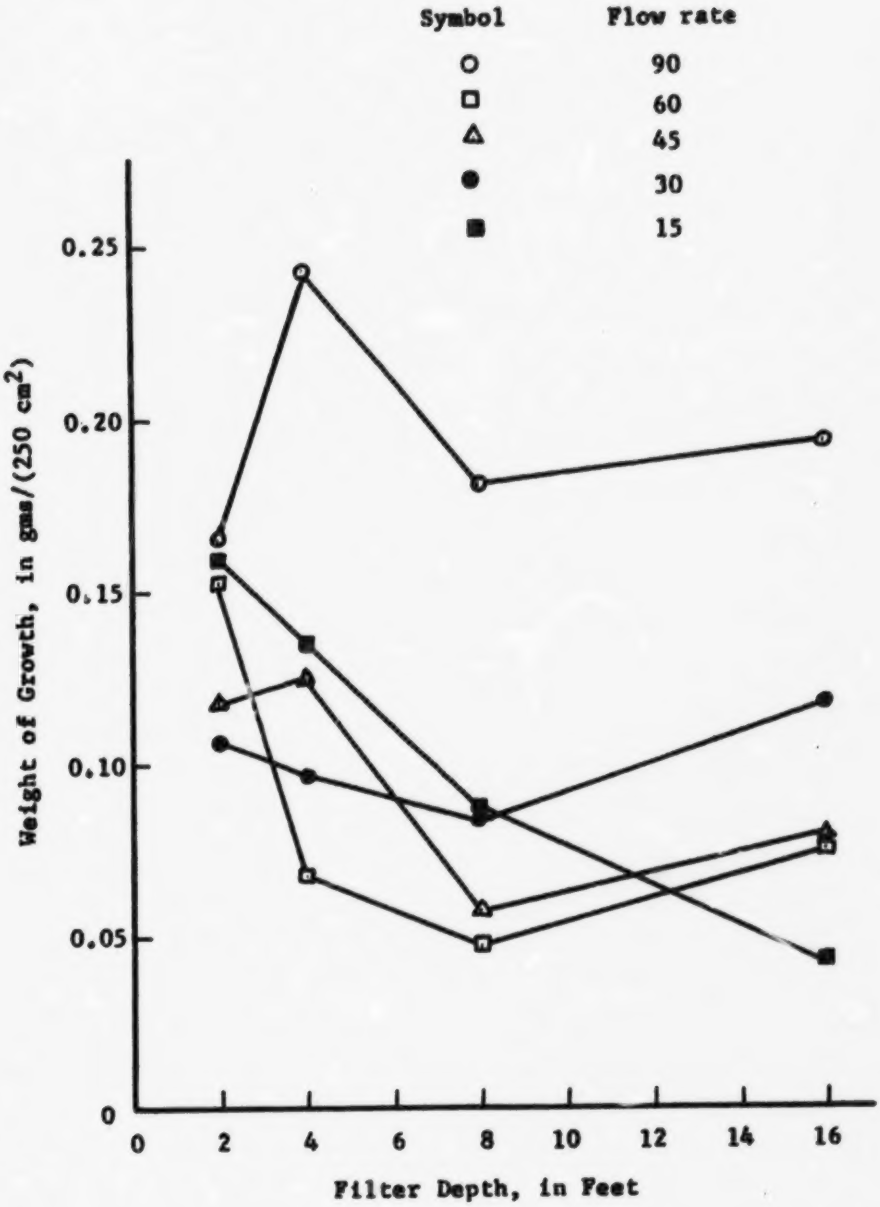

Figure 13. Biological growth versus filter depth for Column III

heavier growth in the bottom levels of the filters is unusual. Generally, more luxuriant growths have been reported to be in the top portions of the filter where food is more readily available. No explanation for the apparent heavier growth in the bottom has been found.

The stripping action of the filter flies can be seen from the growth curves. The fly larvae were first noted at eight-foot level of Column III at the 30 mgad flow rate. From Column III the larvae spread to Column II and permeated the entire depth of both columns at the 15 mgad flow rate. Some larvae were recorded as growth in the growth analysis.

It should be stated that the analysis for growth from a small percentage of the media obtained from the top of a section of the filter may not be a good indication of actual growth conditions in that section. A better indication of the amount of growth would be to mount the filter on a scale and record the change in weight at different flow rates.

Hydraulic Loading. Figures 14 and 15 indicate how contact time varied with hydraulic loading at various depths. From Equation (16) contact time varies inversely with hydraulic loading. A comparison of Equations (15) and (16) shows that the flow rate had a greater influence on contact time for the media with biota than clean media. With clean media the liquid flows through the packing in a defined free space between the media which does not change as

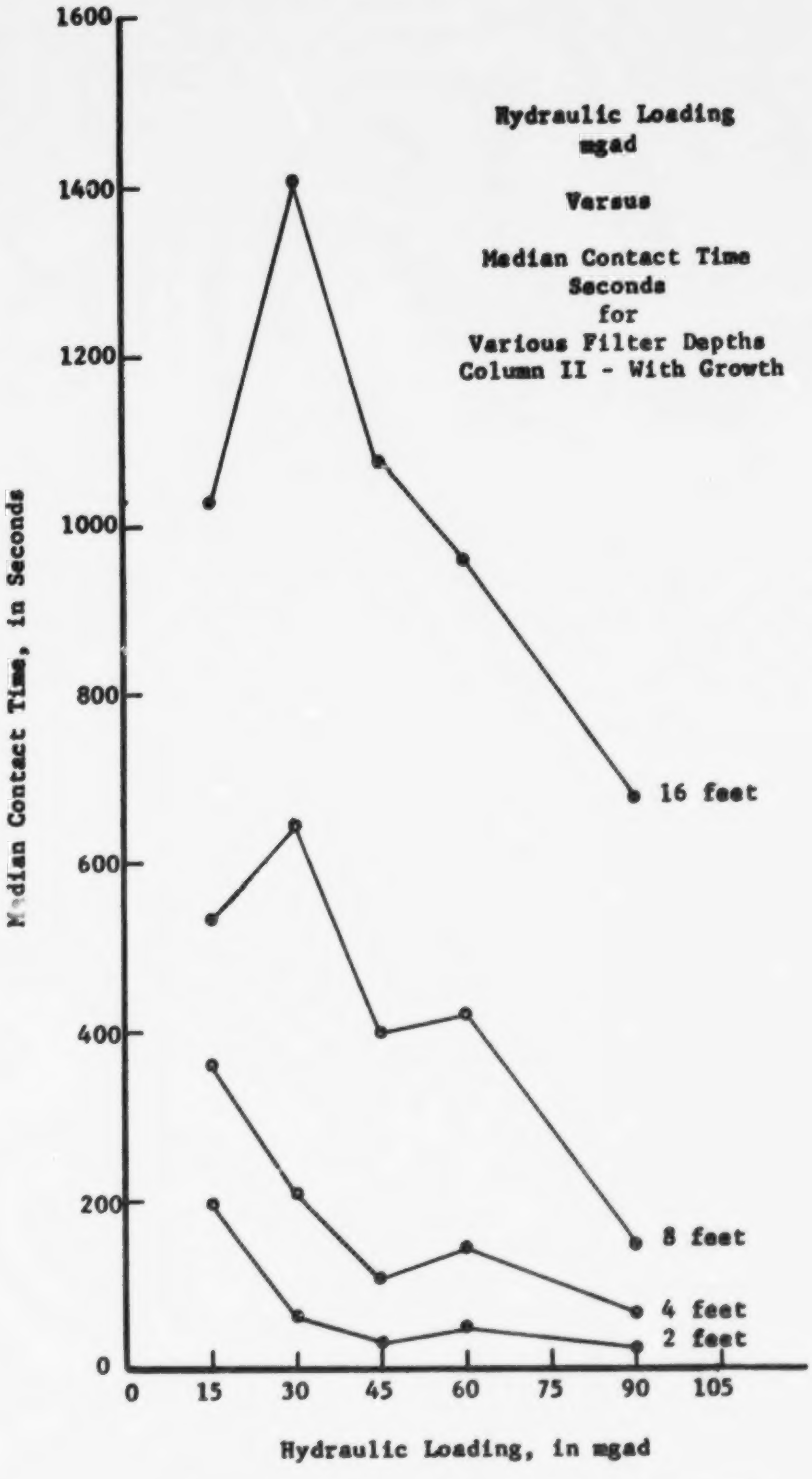

Figure 14. Median Time - Hydraulic Loading

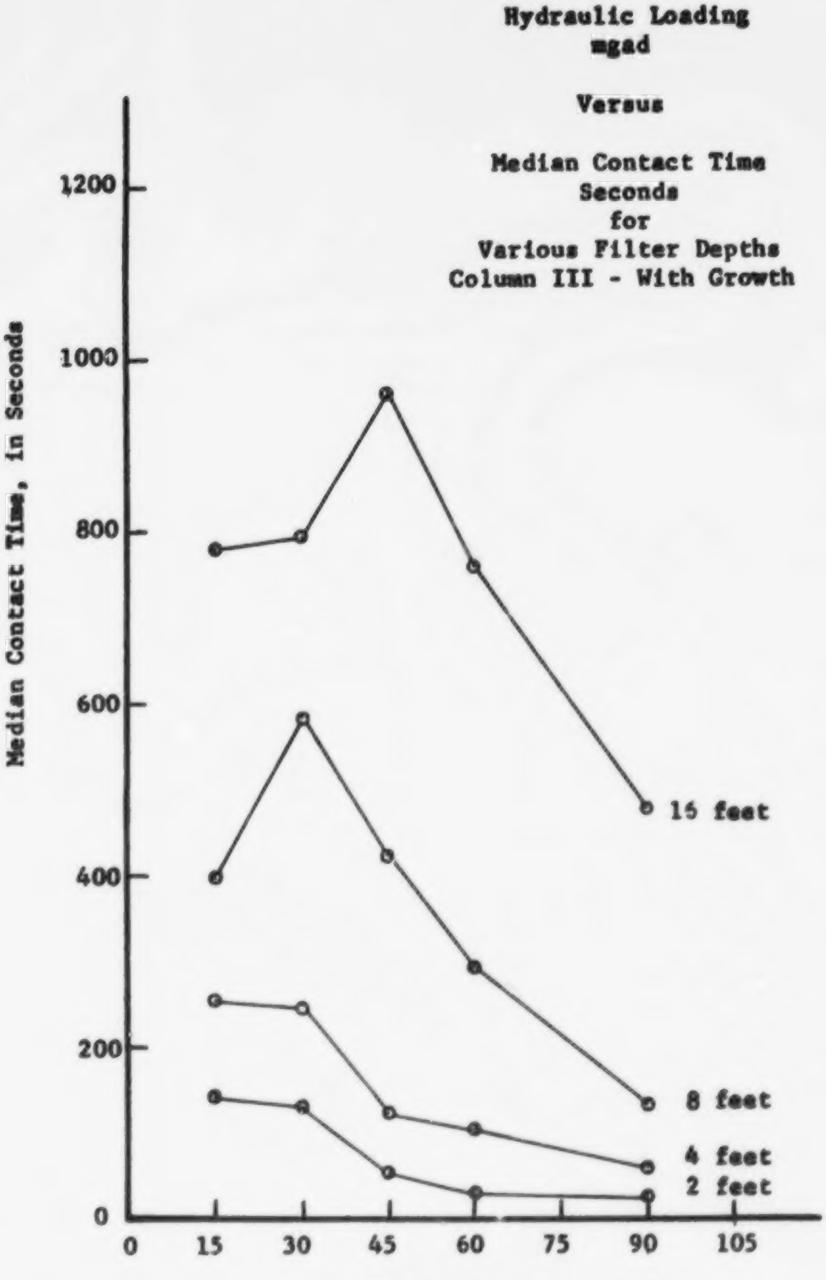

Figure 15. Median Time - Hydraulic Loading

the flow rate is changed. But for the media with growth the space changes as the voids fill with growth. Further, the pattern in which the growth fills the voids depends on the distribution of the liquid in the column. This distribution is dependent on the flow rate and the growth already present. The interplay between flow rate and growth distribution is one explanation of the greater influence of flow rate on the contact time for the media with growth.

A comparison of the exponent m shows an increase from 0.76 for clean media to 1.05 for media with growth. A proportionately larger decrease in contact time results from an increase in flow rate. Channeling is expected where the buildup of growths in the voids divert the liquid to a series of channels in the column. A greater flow through these channels keep the growths scoured and reduces the contact time.

A break in the curves at the 30 mgad flow rate is attributed to the action of the filter fly larvae. The reduction in contact time at 15 mgad resulted from the larvae destroying part of the growths in the voids

Depth. Figures 16 and 17 give an indication how contact time varied with depth at various hydraulic loadings for Columns II and III respectively. Depth had more significance on the determination of contact time than the other variables in either Equation (15) or (16). A comparison between the two equations shows depth has a greater effect on media with growth. The influence of depth as given in

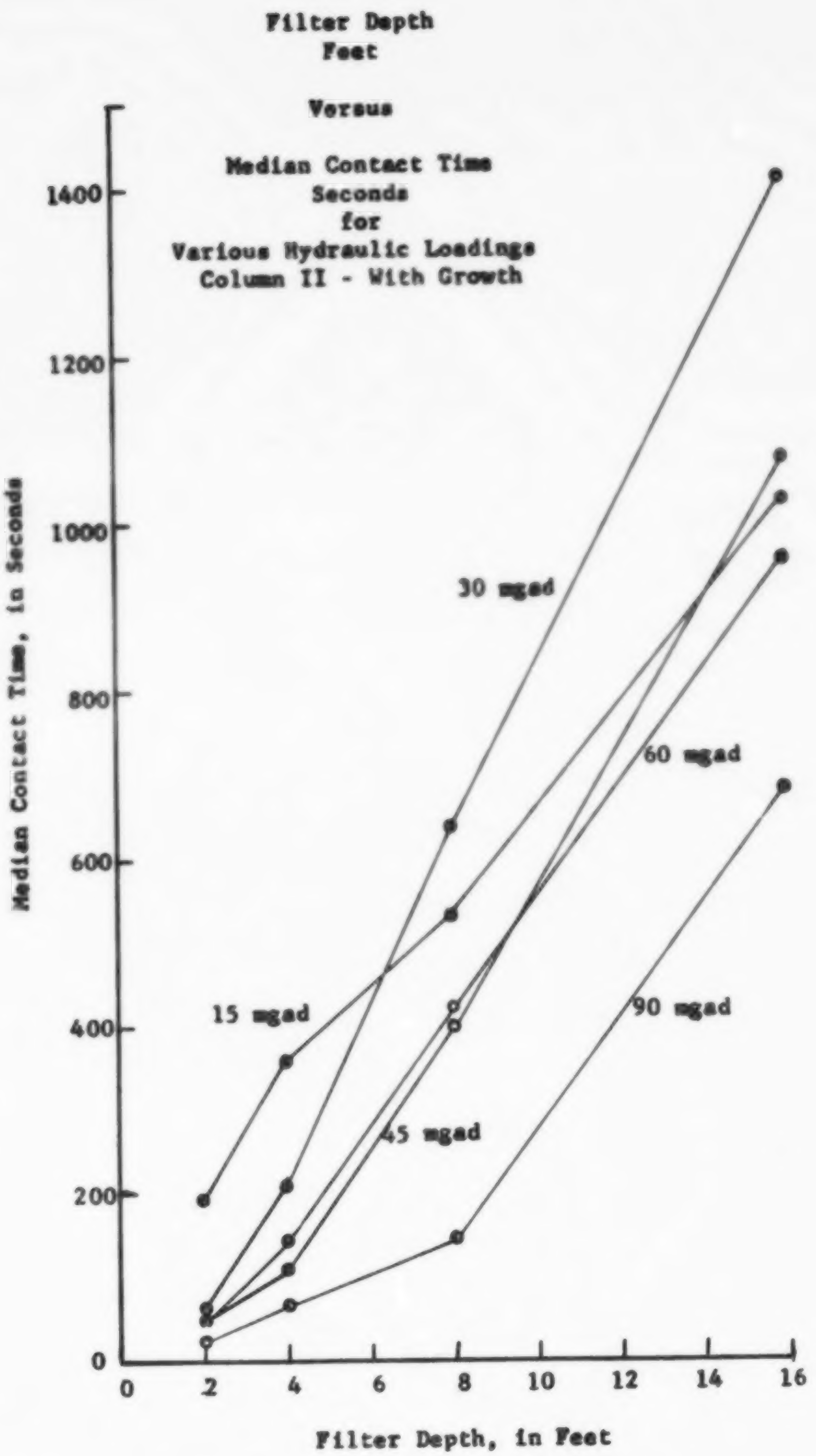

Figure 16. Median Time - Depth

Filter Depth
Feet

Versus

Median Contact Time
Seconds
for
Various Hydraulic Loadings
Column III - With Growth

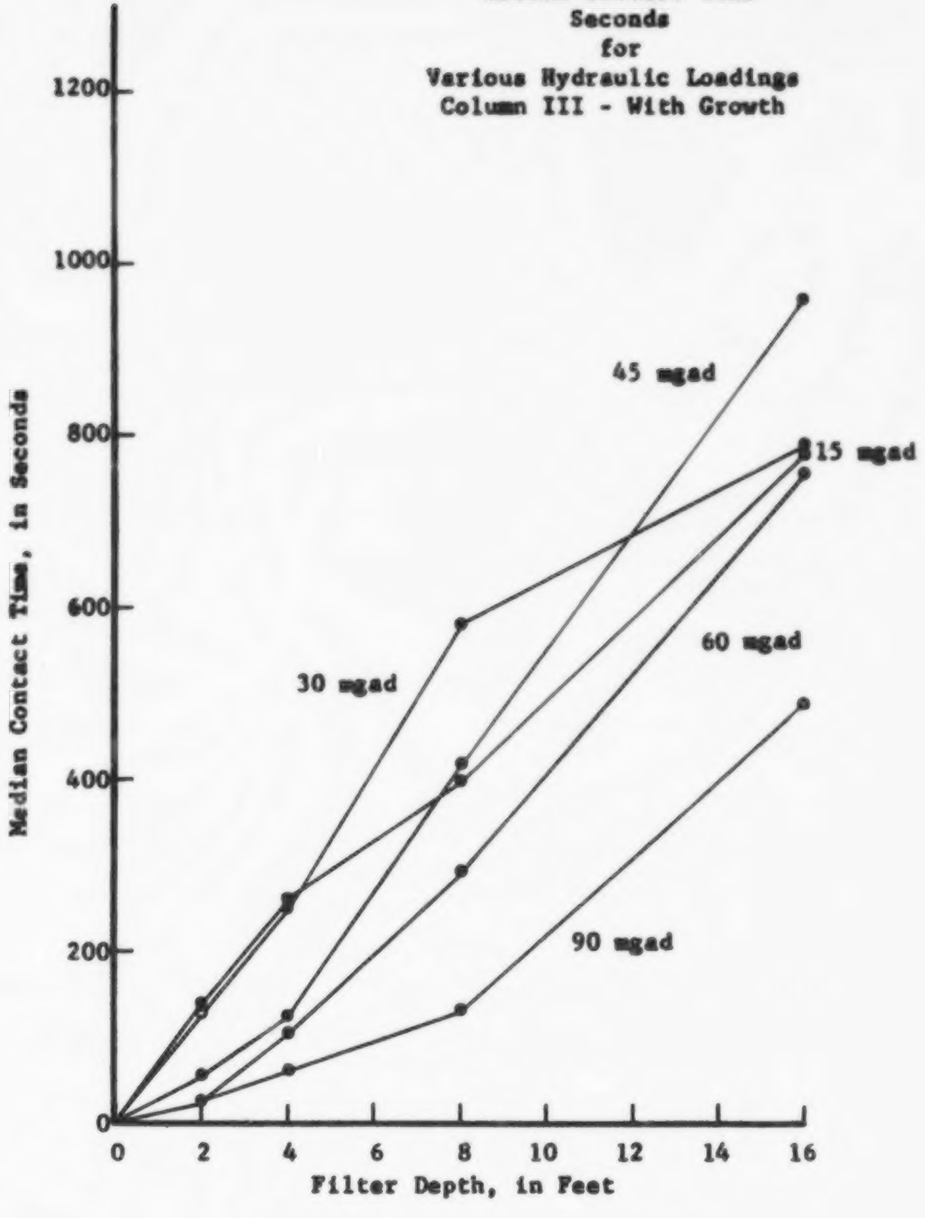

Figure 17. Median Time - Depth

Equation (16) differs from what might be expected. From previous evidence the greater growth would be expected in the top sections of the filters. But from the growth analysis greater growth was encountered at the 16-foot level than at the rest of the levels. If channeling had occurred due to a buildup of growths in the top sections with a better distribution of the liquid at the lower depths a greater contact time could be realized for a section of the column at the lower depths.

Media. As was shown from the analysis of the data, the media size seems to be of little significance as this media becomes covered with a biological slime. A factor that must be considered is that the comparitively small media used in this study provides a general void size such that the growth of the microorganisms could smooth out the effect of the two different media sizes. Whether or not this would be the case for larger media found in present trickling filters would have to be investigated. For this study it is concluded that media size has no influence and this variable will be neglected giving an equation in the form of Equation (17).

Empirical Equation and Experimental Results

A comparison of the curves for the solution of Equation (17) and experimental data is shown in Figure 18. The data points are plotted for both columns since it was determined that the media size does not influence the contact time. The smooth curves are a plot of the

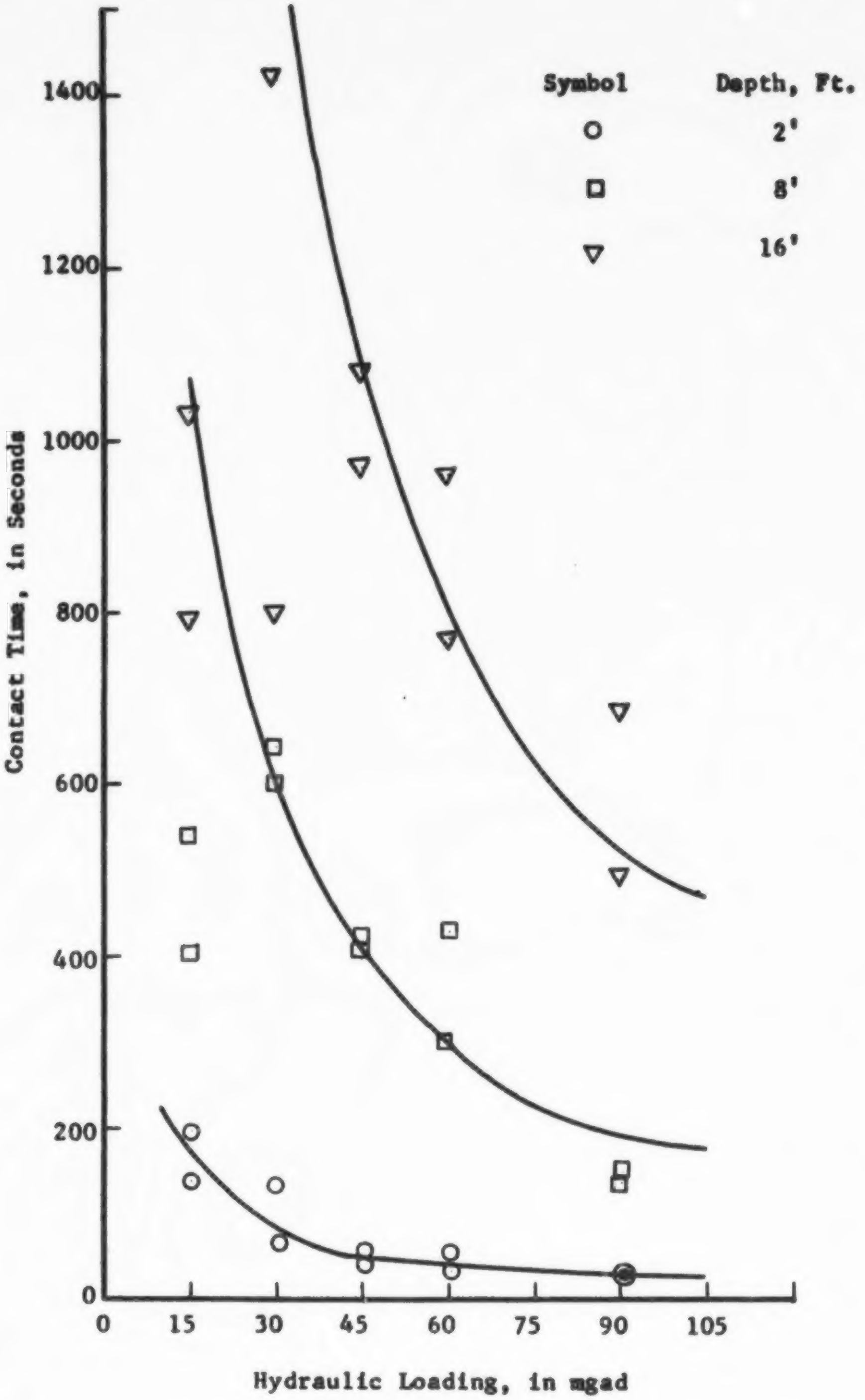

Figure 18. Comparison of empirical equation and experimental data for media with growth.

solution of Equation (17) for the indicated depths. In these plots the experimental data for the 15 mgad at 16-feet and 8-feet have been rejected because of filter flies. The data follows the theoretical curve at lower depths and increasing flow rates closer than at greater depths and lower flow rates.

The useful application of this equation to determine the contact time in any filter will depend on how close the conditions of the biological growths approach the conditions of the growth in this study. It can be seen that the growths can appreciably alter the contact time from that of clean media.

Effect of Contact Time on COD Removal Rates

Experimental Results

Figures 19 and 20 are plots of COD remaining versus filter depth for various hydraulic loadings on the two columns. An examination of the curves show the greatest rate of removal occurs in the top portion of the filter where readily assimilable feed is available. The removal rates then decrease for both columns with increased filter depth as seen by a flattening of the curves past the eight-foot depth.

The greatest effects of flow rate on COD removal rates were observed in the top two feet of the filter. From the plotted values at the two-foot depth the range of COD removal is 57 per cent at 15 mgad for Column II down to 20 per cent at 90 mgad for Column III. As the depth increased the effect of the flow rate on COD removal

Per Cent COD Remaining

Versus

Filter Depth, Feet
for
Various Hydraulic Loadings
Column II

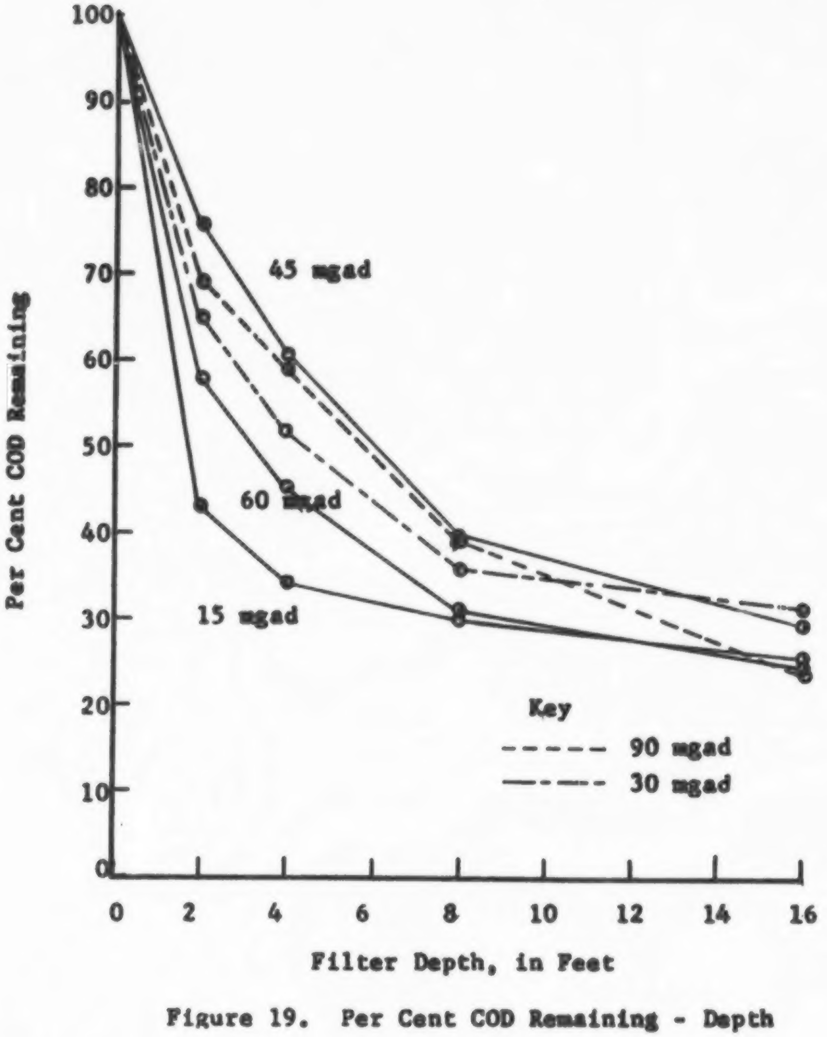

Figure 19. Per Cent COD Remaining - Depth

Per Cent COD Remaining

Versus

Filter Depth, Feet
for
Various Hydraulic Loadings
Column III

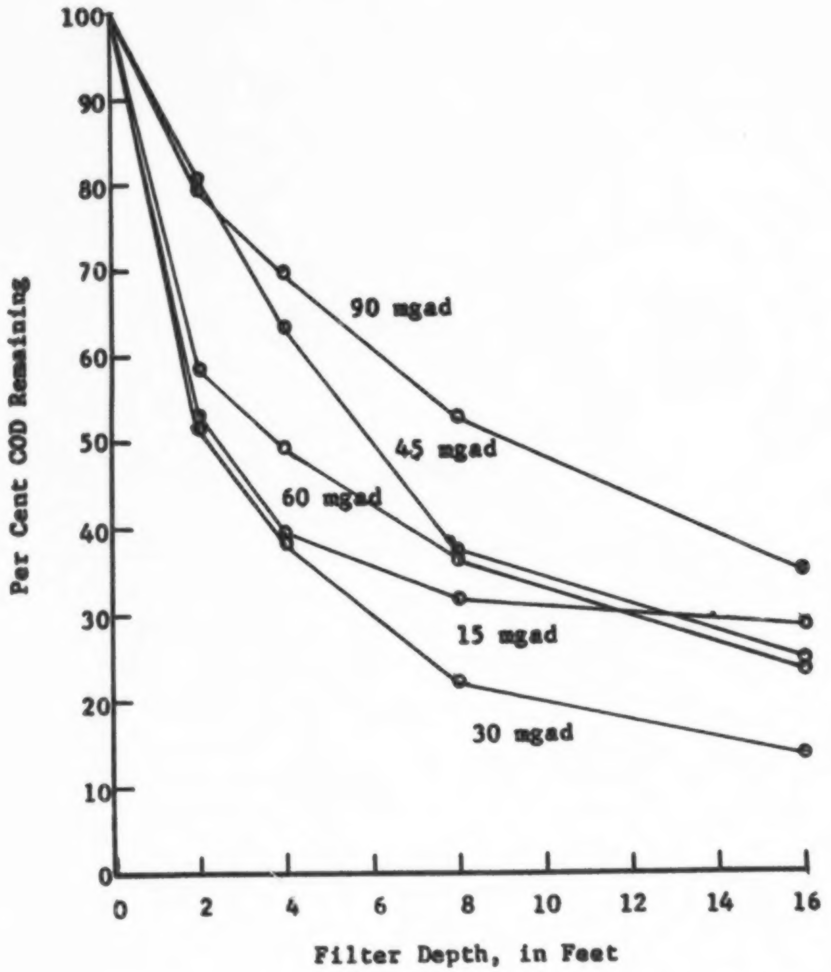

Figure 20. Per Cent COD Remaining - Depth

decreased and the range of values is narrowed down until the COD removal values at 16-feet for Column II are between 69 and 76 per cent. For Column III at 16-feet, the difference in COD removal ranged from 65 to 86 per cent. This narrowing of the range indicates that at higher flow rates greater advantage was taken of the lower depths of the filter for purification. It should also be noted that for Column II at the 16-foot level, six times as many pounds of COD were removed at the 90 mgad flow rate than at the 15 mgad flow rate. This increase in the total pounds of COD removal with increased flow rate was greatest at the lower filter depths.

A comparison of COD removal between the two columns indicates they are generally the same. An exception is that Column II gave better COD removal at the 90 mgad flow rate than Column III. A comparison of the growths at the different flow rates for both columns seems to show little correlation between the amount of growth and the COD removal. It is also difficult to detect from the curves any affect on COD removal due to the filter flies at the 15-30 mgad flow rates. Further examination of the curves indicates in general, that in the top portion of the filters there was a greater COD removal at the lower flow rates than at the higher flow rates.

Empirical Equation for COD Removal

Equation (18) is an empirical equation derived from the analysis of the data of per cent COD remaining as a function of the contact time. The equation does not follow a first order reaction. Most of the postulated first order kinetic equations are based on BOD removal rather than COD removal. Due to the difference in determination of the two values, there is organic material oxidized in the COD determination that is not accessible for biological degradation. Even for these equations based on BOD removal there is evidence that the reaction is not strictly first order and that the removal rate decreases with concentration or time since the easily assimilable components of the feed are removed more readily. Equation (18) follows this retardant form where the removal of COD becomes more difficult with an increase in time. Further examination of the equation shows that total COD removal is not possible. There will be some fraction or a finite COD value that cannot be removed. This fraction of non-removable organic material seems to be true for BOD values and first order reaction also.

The application of the equation can be approached two ways. Given a deep trickling filter with the physical dimensions known, the contact time through the filter can be computed from Equation (17). This time may be used in Equation (18) to find the COD removal that can be expected of the filter at some hydraulic loading rate. The second approach is to specify the desired COD removal and a solution of Equations (17) and (18) will give the size of the filter needed.

SUMMARY

This research encompassed the study of the combined biophysical system of a deep trickling filter system under controlled conditions. The study attempted to correlate the physical factors of media size, depth of filter, and organic and hydraulic loading rates with the biological activity of the filter slime. This correlation was accomplished by evaluating a relationship between the rates of removal in laboratory models of a deep trickling filter with the time of retention of a liquid substrate in these filters.

The experimental filters consisted of three 5.8-inch diameter columns, 18 feet in depth. Each column was packed with a different size of spherical media. The time of retention of a fluid in these filters, using sodium chloride as a tracer, was evaluated as the median residence time. The contact time and organic removal, measured as COD removal, were determined for different flow rates and at various levels in the columns.

An evaluation of the data by a step-wise regression analysis using an IBM 1620 computer established three empirical relationships. Two equations were determined for contact time as a function of flow rate, depth of the filter and media size. The first equation gave a relationship for contact time on media without growth as:

$$t = 207 \frac{D^{1.08}}{Q^{0.76}\ d^{0.50}}$$

where the regression analysis yielded a correlation coefficient equal to 0.99. The second equation provided a relationship for

contact time on media with biological growth as:

$$t = 1072 \frac{D^{1.44}}{Q^{1.05}}$$

where the regression analysis gave a correlation coefficient of 0.98.

The useful application of the first equation is limited to describing the action of different variables on a clean spherical media where conditions could be controlled. The form of this equation served as a guide in developing the second equation. The use of this second equation to determine contact time on any filter will depend on how close growth conditions follow those in this study.

The third empirical equation established a relationship for COD removal as a function of time as:

$$\frac{Pe}{Po} = 1.03t^{-0.19}$$

with a correlation coefficient of 0.91. This equation for COD removal is a retardant form in that organic removal becomes more difficult with an increase in contact time and indicates that there is a fraction of COD which is not removable.

CONCLUSIONS

1. Contact time for a liquid flowing through the filter bed without biota in the range of media size was found to be inversely proportional to the 1.76 power of the hydraulic loading, inversely proportional to the 0.50 power of the diameter of the media, and directly proportional to the 1.08 power of the filter depth.
2. Contact time for a liquid flowing through the filter bed with biota in the range of media size was found to be inversely proportional to the 1.05 power of the hydraulic loading and directly proportional to the 1.44 power of the filter depth.
3. Contact time is not influenced by media size for filter media covered with biota.
4. Flow rate has a greater influence on contact time for media with biota than for the media without biota.
5. Depth has more influence on contact time than any other variable for media both with and without biota.
6. Depth has a greater effect on contact time for the media with biota than the media without biota.
7. The fraction of COD remaining is inversely proportional to the 0.19 power of the contact time.

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APPENDIX III

REPRINTS OF PUBLISHED ARTICLES

Engineering Experiment Station
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Reprint No. 64

PERSULFATE OXIDIZABLE CARBON AND BOD AS A MEASURE OF ORGANIC POLLUTION IN WATER

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By

C. M. Gilmour, Bacteriology Department
F. Merryfield
L. Purkerson
F. J. Burgess
J. K. Carswell
Civil Engineering Department

Persulfate Oxidizable Carbon and BOD as a Measure of Organic Pollution in Water[1]

C. M. GILMOUR, F. MERRYFIELD, F. BURGESS,
L. PUNKERSON, and K. CARSWELL
Professor of Bacteriology, Sanitary Engineering and Graduate Assistants
Department of Bacteriology and Engineering Experiment Station
Oregon State College
Corvallis, Oregon

The measurement of organic pollution in water has been the subject of numerous investigations. Several analytical approaches have been used including nitrogen transformations, biological oxygen depletion and chemical oxygen demand. Today the accepted procedure for the determination of organic pollution is the BOD which measures the oxygen consumed by microorganisms during the utilization of organic nutrients. Space does not permit a prolonged discussion of the BOD test. It is sufficient to comment that notwithstanding the inherent problems of sewage dilution effects, elapsed time, interfering nitrification reactions and variation in oxidation rate constants, that the biological oxygen demand test stands as the primary procedure for the determination of readily oxidizable carbonaceous matter in water.

Since the acceptance of the BOD test investigators have long sought a procedure which would provide compatable data in a shorter period of time. In general these studies have taken the form of a search for suitable chemical oxidants (2). Four such oxidants have received careful attention; namely potassium permanganate, potassium dichromate, ceric sulfate and iodic acid.

Unfortunately the above chemical methods provide oxygen demand data that does not directly correlate with the biological oxygen demand (2,5). This finding is understandable, however, when it is remembered that such chemical oxidants react with a wide variety of both stable and unstable organic matter fractions thereby giving higher oxygen demand values. As a consequence, it has been recommended that chemical oxidation methods be used only when estimating the strength of trade wastes and under conditions where the BOD cannot be determined.

In the present study data are presented on the use of potassium persulfate for the oxidation of organic substrates present in polluted waters. The results obtained by the use of this chemical oxidant differ in several important respects from any previously used oxidizing agent. As reported by Osborn and Werkman (4) and later modified by Katz et al. (1) the persulfate oxidation can be used only for water-soluble organic compounds. This observation immediately suggests therefore that the persulfate procedure might detect only the first stage, unstable organic moeities normally measured by the five-day BOD method. The complex carbonaceous fractions such as cellulose, ring compounds, long chain fatty acids, and various proteins would be largely excluded. Of additional importance was the observation of Osborn and Werkman (4), that the procedure may be carried out in the presence of mineral chlor-

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[1] Supported by a research grant EG-6408 from the National Microbiological Institutes of the National Institutes of Health, U.S. Public Health Service.

ides, chlorine, sulfur, and nitrogen containing compounds. It is interference of this kind which has subjected the dichromate method (3) to some degree of criticism.

A final point relates to the expression of data. As was amply stated long ago by Mohlman and Edwards (2), "If a satisfactory method for carbon could be perfected the results would be correlated more closely with the actual oxygen requirements of the sewage than any correlation possible between the nitrogen and oxygen requirements." These workers using chromic acid as the oxidant presented useful data, the only problem being the complexity of the test and the fact that chromic acid can detect carbon normally utilized beyond the first stage of sewage decomposition. In the present paper, direct carbon values are correlated with the five-day BOD to give a regression coefficient (b_0) capable of being used as a conversion factor for a predicted five-day BOD.

EXPERIMENTAL METHODS

Samples

In order to establish accurate carbon levels in sewage various stock solutions containing known amounts of carbon were made up. The test substrate was dissolved in carbonate free distilled water just prior to use. All stock solutions including carbohydrates, fatty acids and amnio acids were made up so as to contain 25 mg of carbon per ml. This proved to be a convenient amount for subsequent BOD dilutions and the persulfate test. The above stock carbon concentration was established for single compounds, groups of compounds or group mixtures. In this way comparable recovery data could be easily observed. The range in compounds tested are shown in Tables I and II.

TABLE I

CARBON RECOVERIES BY PERSULFATE OXIDATION OF KNOWN SUBSTRATES IN AQUEOUS SOLUTION*

Substrate	Added mg C/ml	Recovered mg C/ml	Per Cent Recovery*
Glucose	2.00	2.11	105
	5.00	4.95	99
Butyric acid	2.00	2.11	105
	5.00	4.80	96
Propionic acid	2.00	2.19	109
	5.00	5.10	102
Ethanol	2.00	2.03	101
	5.00	5.12	102
Lactose	3.00	2.95	98
	5.00	5.02	100
Sucrose	2.00	2.16	108
	5.00	4.95	99
Acetic acid	2.00	1.98	99
	5.00	4.49	90

* Coefficient of variation ranged between 0.7 to 5.3 per cent average 3.0 per cent.

TABLE II

CARBON RECOVERIES BY PERSULFATE OXIDATION OF SUBSTRATE MIXTURES IN AQUEOUS SOLUTION

Substrate	Added mg C/ml	Recovered mg C/ml*	Per Cent Recovery (average)
Mixture A			
Butyric acid Propionic acid Ethanol Sucrose Glycerol	5.0	4.72	94.5
Mixture B			
Sucrose Glucose Xylose Arabinose Lactose	5.0	5.14	102.5
Mixture C			
Leucine Asparagine Glutamate Glycine Aspartate	5.0	4.68	93.6
Mixture of A, B, and C	5.0	4.99	100.0

* Average of three determinations.

Sewage waste samples were also collected in order to check the precision of the BOD against predicted values and to study the range in carbon levels. These included domestic sewage, cannery waste (beans, beets, corn), slaughter house waste, plywood plant waste and sulfite waste liquor. The liquid waste was collected in appropriate bottles, stoppered and then subjected to the BOD and persulfate test within a matter of several hrs (usually two-four hrs).

BOD Test

The five-day BOD test as outlined in "Standard Methods" (5) was used. Aliquots for analysis were placed in 300 ml incubation bottles according to the direct dilution technique and the dilution water containing the required salts added. With the higher carbon levels, dilutions were carried out in volumetric flasks prior to adding to the incubation bottle. A raw domestic sewage seed was used for all experiments involving the added carbon compounds. Glucose and other carbon sources were added at calculated levels along with the seed. Cannery waste runs were self-seeded whereas the sulfite waste liquor, after pH adjustment to 7.2, were seeded with raw domestic sewage. Only those dilutions falling in the range of 40 to 90 per cent oxygen depletion were considered. A statistical analysis of the BOD experiments showed a range in the coefficient of variation of five-15 per cent.

PERSULFATE OXIDATION TEST

The apparatus suggested by Katz et al. (1) was used with minor modifications. As is shown in Figure 1, either a 50 or 125 ml Erlenmeyer type flask may be used. The flask is fitted with a center well, large enough to receive

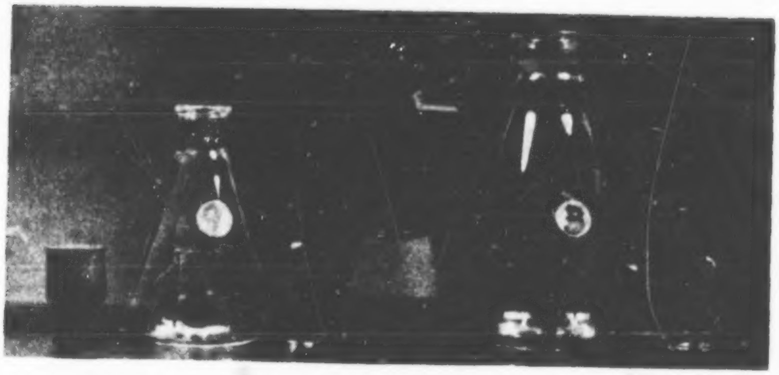

Figure 1 - Glass apparatus used for the persulfate oxidation test.

a glass vial for carbon dioxide absorption. The vial has two attached prongs to facilitate removal by either metal or glass tongs. A rubber serum cap completes the flask assembly.

A sample is pipetted into the flask, the volume adjusted to 10-15 ml with carbonate free distilled water and 0.3 ml of five N H_2SO_4 added. The addition of acid liberates any free carbonate or bicarbonate. Then after swirling the flask gently, 1.0 ml of four per cent $AgNO_3$ is added to precipitate free chlorides. Approximately 0.5 to 0.6 g of potassium persulfate are then added to the flask swirled to distribute the persulfate. About one ml of five N NaOH (CO_2-free) is added to the center well vial and the vial placed in the center well by means of the tongs. The serum cap is now wetted and tightly fitted at the neck of the flask. The vessel is evacuated by inserting a 20-gauge hypodermic needle through the rubber stopper. This step effects removal of any dissolved carbon dioxide. The flask is then placed in an oven at 75 C for one-two hrs. After cooling, the serum cap is removed and the contents of the center well vial washed into a 150 ml Erlenmeyer flask. The volume is brought up to 40-50 ml after which five ml of the precipitating mixture is added ($BaCl_2 \cdot 2H_2O$ - 122·2 g; NH_3Cl - 53.0 g in one liter water). The resulting $BaCO_3$ percipitate may then be caught in a tared ultra-fine sintered glass filter, dried and weighed. Carbon may then be calculated from the obtained weight of $BaCO_3$. The described gravimetric procedure was used throughout the entire study. However, the carbon dioxide absorbed in the NaOH may also be determined by direct titration through the pH range of 8.34 to 4.6.

Should larger samples become necessary the 150 ml size vessel may be used. The smaller flask volume has given accurate carbon levels up to 10.0 mg whereas the larger flask has given good recoveries up to 25.0 mg carbon. Reagents are normally added at twice the given concentration, whenever the 50 ml flask was used.

EXPERIMENTAL RESULTS

Carbon Recoveries

Organic pollution in water includes a wide variety of oxidizable, water soluble carbon compounds. It was considered essential therefore to supply data relative to the efficiency of carbon recoveries given by the persulfate test. The substrates were selected as being representative of the types of carbon compounds oxidized during the first stage of sewage stabilization or in other words directly responsible for the five-day biological oxygen demand. Typical carbon recoveries are shown in Table I. It is quite evident that sufficiently accurate carbon recoveries have been attained. The average coefficient of variation was 3.0 per cent. A further check on the persulfate method is shown in Table II. These experiments were designed so as to provide data on carbon recoveries obtained when mixtures of carbohydrates, fatty acids and amino acids were tested. It is again apparent that the described oxidation procedure is acceptable from the recovery viewpoint and indeed would appear to satisfy the original objective of being able to give a quantitative measure of first stage BOD carbon.

Correlation of Carbon with BOD

As described under methods, various carbon levels (0.05, to 0.5 mg/ml) were established in BOD incubation bottles so as to give a reasonable range in BOD values. In general the final carbon levels in the BOD vessels contained one-tenth the amount of carbon used for the persulfate test. Very little time lag (10-20 min) was allowed between the initiation of the BOD test and the carbon recovery test. The results of these studies are shown in Figure II. A highly significant positive correlation of 0.998 was obtained for the carbon and BOD relationship when using either the synthetic sewage (Mixture A, B, C shown in Table II) or the domestic sewage waste. However, the regression coefficient b_0 of 1807.0 obtained with the synthetic sewage was considerably greater than was calculated for the domestic sewage ($b_0 = 1383.2$). It appears probable that these differences may be partially explained on the basis of a greater velocity rate constant (k) for the synthetic sewage than was observed with the domestic sewage. It is evident, however, that in either case a significant straight-line relationship exists between the carbon level as measured by the persulfate test and the BOD determination. This observation made possible the use of the derived regression coefficients for the prediction of the five-day BOD index.

Actual and Predicted BOD

Upon completion of the method calibration it was decided to test the validity of the predicted BOD value by checking a rather diverse group of sewage materials. Carbon determinations and the five-day BOD tests were initiated at the same zero time. After approximately 12 hrs, a predicted BOD value was established on the basis of the equation $Y = \text{BOD} = b_0$ (mg/C/ml) which after five days was compared with the actual or real value. The results tabulated in Table III call attention to several points of interest. It is clear that with the exception of the stronger wastes such as sulfite waste liquor and the

TABLE III

OBSERVED ACTUAL AND PREDICTED BOD VALUES

Sewage Type	Carbon mg/ml	Actual BOD mg/L	Predicted 1*	BOD 2*
Raw Domestic	0.083	114	114	150
Bean waste (lagoon)	0.152	188	210	274
Bean cannery waste (river)	0.044	55	60	79
Cannery waste (beets)..........	1.640	2100	2268	2963
Slaughter house (meat)	2.50	3760	3458	4517
Plywood glue waste	6.00	13110	22131	28912
Pulp and paper waste	33.40	20220	46198	60353

*1 Calculated on regression coefficient for domestic sewage 1383.2 (mg C/ml) = BOD

*2 Calculated on regression coefficient for 15 compound carbon mixture 1807 (mg C/ml) = BOD plywood glue that the predicted values fall very close to the actual BOD of the test sewage. The predicted BOD range fell approximately between 50 and 3500 mg/l. This is not to say, however, that the very high predicted BOD's shown for the waste sulfite liquor and plywood glue do not reflect the true BOD of these wastes. As is well recognized, the usual five-day BOD test runs on such high strength wastes is more often erroneous than correct. Predictions based on the b_0 of the synthetic sewage always gave higher values and have been included for comparison purposes.

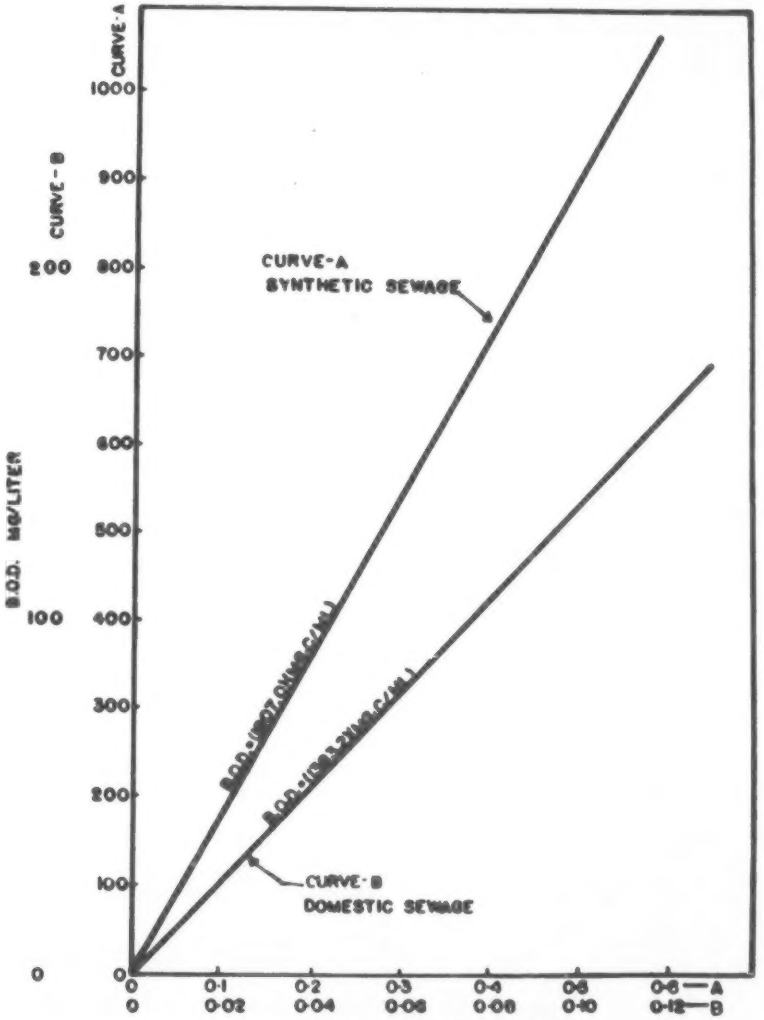

Figure 2 - Regression coefficient lines for carbon and BOD with synthetic and domestic sewage.

DISCUSSION

The question of the possible use of direct carbon determinations in place of the usual five-day BOD has been investigated. The underlying principle (bacterial oxidation of water-soluble carbon) of the first stage sewage stabilization process as reflected by the five-day BOD has been further corroborated by the results of this study. Otherwise the given predicted values would not have correlated with the actual BOD determinations. Thus the persulfate recoverable carbon fraction undoubtedly lies very close in nature to the carbon oxidized by bacteria during the five-day BOD. This finding places the persulfate procedure in a category quite different to that occupied by other chemical oxidation procedures. In view of the over-all simplicity of the persulfate method one might conclude that the suggested procedure has potential future value in the water pollution field. The advantages of the persulfate method being: less time consumed, fewer materials and probably more accurate test standardization.

Since the carbon recovered by the persulfate test may immediately be expressed in terms of BOD, then it appears likely that either the carbon value itself or the related BOD may be used for the calculation of sewage loading data. This applied aspect of the study is presently being investigated by the use of an experimental deep trickling filter.

SUMMARY

The following points summarize the essential findings of the study:

1. The persulfate oxidation procedure gives excellent recoveries of a wide variety of water soluble compounds including carbohydrates, fatty acids, alcohols, and amino acids.

2. A high correlation exists between persulfate oxidizable carbon and the five-day BOD index.

3. It is possible, on the basis of a derived regression coefficient, obtained with increasing increments of carbon and related BOD values to predict the five-day BOD. The predicted BOD value is obtained in 10-12 hrs after completion of the direct carbon determination.

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EVALUATION CRITERIA FOR DEEP TRICKLING FILTERS

By F. J. BURGESS F. MERRYFIELD J. K. CARSWELL
Civil Engineering Department
C. M. GILMOUR, Bacteriology Department

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F. J. Burgess, C. M. Gilmour, F. Merryfield, and J. K. Carswell

Editor's note: Filter loading rates are reported in this paper as million gallons per acre per day (mgd/acre) and pounds BOD per acre-foot per day (lb/day/acre-ft). To convert to the recommended units of gallons per day per square foot (gpd/sq ft) and pounds BOD per day per 1,000 cubic feet (lb/day/1,000 cu ft), given in "Units of Expression for Wastes and Waste Treatment," Manual of Practice No. 6, Water Pollution Control Federation, Washington, D. C. (1958), use the following:

million gallons per acre per day × 23 = gallons per day per square foot

pounds BOD per acre-foot per day × 0.023
= pounds BOD per day per 1,000 cubic feet

Where BOD is intended to be reported as other than 5-day it is marked: i.e. 20-day.

Increasing populations, together with the trend toward metropolitan centers and the expansion of complex liquid waste-producing industries, have emphasized the necessity of conserving the nation's water resources to supply the needs of its population and industries. An appraisal by the U. S. Public Health Service (1) indicates the urgent need for extending the frontiers of knowledge to combat the water pollution control problem. Of particular importance to sanitary engineers is the necessity of developing new methods of waste treatment and evaluating parameters of loading and criteria of performance for existing methods.

Objectives

Although numerous papers on performance and theory have appeared in the literature, certain phases of biological filtration still are not fully defined, and the validity of theoretical considerations needs testing.

Trickling filter research was begun in 1957. A long-term goal of the research program is to obtain a more fundamental understanding of physical and biological mechanisms of waste treatment and the problems related to their application.

The following specific objectives were of immediate concern in the trickling filter project and are the subject of this paper:

1. To determine operational characteristics of a deep trickling filter over the wide range of loadings reported in the literature (2) (3) (4) on the relatively weak wastes typical of the area in order to determine the applicability of design standards for this case.
2. To evaluate the reliability of measurement indexes for testing treatment efficiency and loading, with particular emphasis on the relation of water-soluble carbon and BOD.

Research Facilities

Test facilities necessary for carrying out specific objectives of this research were constructed at the Corvallis (Ore.)

F. J. Burgess, C. M. Gilmour, F. Merryfield, and J. K. Carswell are, respectively, Associate Professor of Civil Engineering, Professor of Bacteriology, Professor of Sanitary Engineering, and Research Assistant, at the Engineering Experiment Station, Oregon State University, Corvallis, Ore.

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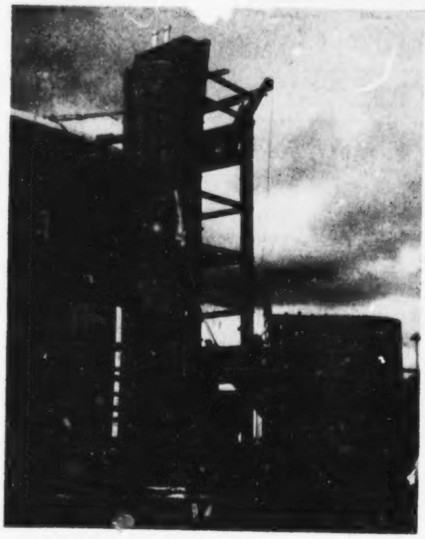

FIGURE 1.—Test filter installation.

sewage treatment plant (Figure 1). They consist of a primary and a secondary clarifier designed at an overflow rate of 1,040 gpd/sq ft and a 1.25-hr detention time for a flow of 20 gpm. Variable flow primary and secondary pumping units of 30-gpm maximum capacity each provide for filter dosing rates from 0 to 300 mgd/acre and recirculation values as high as 10 to 1, which are controlled through an automatic distribution system. The filter unit is 4 ft in diameter and 20 ft deep, with sampling ports at 2-ft intervals. Filter media consist of clean, rounded river rock screened from 2.5 to 4 in. A test of filter media as delivered and placed indicated an average length of 4.9 in., with an average width of 2.2 in. and a porosity of the packed bed of 48 per cent. Filter ventilation by natural convection was used and later proved adequate; gas analysis during the testing program indicated oxygen concentrations throughout the filter to be near atmospheric.

Because of limited funds and the nature of the objectives, multiple treatment units with known surface areas and more closely controlled conditions were deferred until a later date, and will be included in the next phase of the research.

Analytical Methods

To determine operational data, samples of raw waste, filter influent, and effluent from the sampling ports were composited for immediate analysis, and filter flow and mean residence time (Figure 2) were determined. Increments of change in loading rates applied between test series were small and sufficient time was permitted between changes for stabilization of the filter zooglea before subsequent testing.

Test procedures included analyses for 5- and 20-day BOD, dissolved oxygen, ammonia, nitrite- and nitrate-nitrogen, pH, temperature, and water-soluble carbon. Except for the latter, methods for analyses are described in "Standard Methods" (5) and are not discussed further.

Water-Soluble Carbon Test

Earlier work (6) indicated a strong correlation between water-soluble carbon determined by persulfate oxidation and carbonaceous organic material normally measured in part by 5-day BOD. As reported by Osborn and Werkman (7) and later modified by Katz *et al.* (8), persulfate oxidation can be used for water-soluble organic compounds. Complex carbonaceous fractions such as cellulose, ring compounds, long-chain fatty acids, and certain proteins are largely excluded. The persulfate reaction may be carried out in the presence of mineral chlorides, chlorine, sulfur, and nitrogen-containing compounds that normally interfere with other oxidation tests.

Apparatus for the test consists of either a 50- or 125-ml Erlenmeyer flask fitted with a glass center well large enough to receive a glass vial for holding the CO_2 absorbent.

A 30-ml sample of waste is pipetted into a 125-ml flask and 1.0 ml of 5N

H_2SO_4 is added. Addition of acid lowers pH to the range of 1 to 2 for most wastes and liberates free carbonate or bicarbonate compounds. After gently swirling the flask, 2.0 ml of 4-per cent $AgNO_3$ is added to precipitate free chlorides. Approximately 1.0 g of potassium persulfate is then added and the flask is swirled gently to distribute the persulfate. One to 2 ml of $5\underline{N}$ NaOH (CO_2-free) are added to the center well vial, allowing approximately ¼-in. freeboard, and the vial is placed in the center well by means of a wire hook. A serum cap is wetted and tightly fitted at the neck of the flask. The vessel is evacuated by inserting a 20-gage hypodermic needle through the rubber serum cap and connecting it to a vacuum source. This step effects removal of any dissolved CO_2 and CO_2 liberated from carbonate and bicarbonate compounds by the acidification step.

The flask is then placed in an oven at 75°C for 2 hr. After cooling, the serum cap is removed and the contents of the center well vial are washed into a 150-ml Erlenmeyer flask. The volume is brought up to 50 ml, after which 5 ml of the precipitating mixture are added. The precipitating mixture is prepared by dissolving 122.2 g of $BaCl_2 \cdot 2\,H_2O$ and 53.0 g of NH_4Cl in 1 l of distilled water. The resulting $BaCO_3$ precipitate then may be caught in a tared ultrafine sintered glass filter, dried, and weighed. A minimum of three blanks should be prepared for each test series using carbonate-free distilled H_2O. Carbon then may be calculated from the obtained weight of $BaCO_3$ by the following formula:

$$\text{mg carbon/liter} = \frac{(\text{wt BaCO}_3 - \text{blank})\ 1{,}000}{(16.432)(\text{sample size ml})} \quad \ldots (1)$$

The described gravimetric procedure was used throughout the study. The CO_2 absorbed in the NaOH, however, may be determined by direct titration through the pH range of 8.34 to 4.6.

Sensitivity of the test was determined by testing known compounds. Average departure of carbon recovery for such tests was 3.4 per cent and the standard deviation was 4.6 per cent, indicating good sensitivity (6).

Relationship of water-soluble carbon and BOD is a function of waste characteristics. Because BOD follows the basic "biological oxidation law" developed by Phelps (9), it can be defined for the first-stage reaction by the differential form

$$-dL/dT = KL \quad \ldots\ldots (2)$$

from which the familiar

$$\text{BOD} = L(1 - 10^{-KT}) \quad \ldots\ldots (3)$$

evolves, in which L is ultimate first-stage BOD, T is time in days, and K is rate constant.

Because the rate constant K will vary depending on waste characteristics, water-soluble carbon may bear a more direct relationship to ultimate first-stage BOD than to 5-day BOD. The value of L, however, can only be measured as a theoretical value, and methods for its determination can lead to significant test errors. If, for example, the carbonaceous material level were such that $L = 100$ mg/l, a 5-day

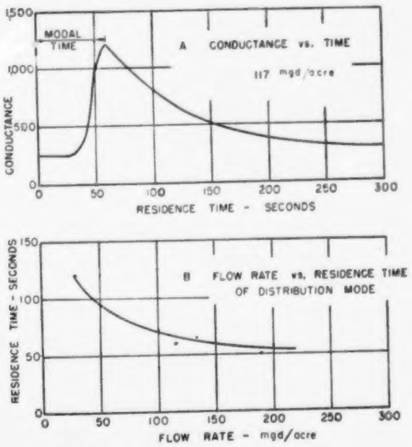

FIGURE 2.—Residence time vs. flow rate.

TABLE I.—Loading Data for Test Series

Flow (mgd/acre)	BOD Loading (lb/day/acre-ft)	Recirculation Ratio	BOD Removal (lb/acre-ft)	BOD Work Rate (lb/day/acre-ft)				Temp. Infl. (°F)	BOD (mg/l)		NH_3-N (mg/l)		NO_3-N (mg/l)		NO_2-N (mg/l)		Water-Soluble Carbon (mg/l)	
				0–5 Ft	5–10 Ft	10–15 Ft	15–20 Ft		Infl.	Effl.	Infl.	Effl.	Infl.	Effl.	Infl.	Effl.	Infl.	Effl.
24.8	885	0	637	167	1,812	464	332	54	85	24.0	—	—	—	—	0.6	8.0	—	—
30.0	1,500	0	565	51	779	700	450	56	120	75.0	—	—	—	—	0	3.8	—	—
20.0	918	1.0	860	1,730	1,040	180	133	43	110	12.0	—	—	—	—	—	—	—	—
12.0	325	1.0	286	815	194	100	40	51	65	8.0	—	—	—	—	—	—	—	—
24.4	770	1.0	645	1,870	715	85	0	64	76	12.0	—	—	—	—	0.5	15.6	—	—
12.2	535	0	372	457	750	460	0	61	105	32.0	—	—	—	—	0.2	14.6	—	—
20.0	392	1.0	270	865	230	90	0	—	47	15.0	—	—	0.03	0.3	0.1	1.8	—	—
9.5	275	1.0	245	910	77	55	0	—	70	8.0	—	—	0.02	1.2	0.2	6.2	—	—
117.0	975	5.0	230	400	278	135	0	66	23	15.3	5.0	5.0	0.8	1.0	1.45	1.5	0.0302	0.0229
59.0	816	0	322	300	500	480	0	63	33	20.0	4.5	3.5	0.09	0.08	—	—	0.0345	0.0240
190.0	2,645	1.0	1,140	6,600	0	0	0	68	66	37.5	8.7	8.6	0.1	0.18	0	0	0.0856	0.0599
134.0	436	4.0	165	740	360	0	0	65	39	16.0	6.5	8.0	0.04	0.56	0.5	1.6	0.063	0.0385
200.0	4,880	0.5	1,400	1,450	1,750	400	0	67	90	64.0	12.0	12.0	0.01	0.6	0	0	0.100	0.075
24.0	1,280	1.0	1,080	2,960	520	365	156	66	128	28.0	—	—	0.01	0.01	0.4	0.3	—	—
24.0	700	1.0	540	1,760	150	217	0	67	70	16.0	—	—	0.01	0.1	0.2	0.2	—	—
24.0	400	1.0	300	960	230	136	0	66	40	10.0	—	—	0.02	0.8	0.2	3.8	—	—
167.5	4,600	0	420	1,700	855	0	0	68	66	60.0	4.5	4.0	0	0	0	0	0.065	0.0622
157.0	1,435	1.6	688	340	183	261	0	69	27	19.0	5.0	5.0	1.45	2.0	0.28	0.32	0.038	0.05

BOD value of 80 mg/l might be observed if $K = 0.14$, and $L = 50$ mg/l might be observed at $K = 0.06$. Fortunately, the range of K-values is generally small for a given situation, and the water-soluble carbon test may be correlated with BOD if it is desired to express-values in terms of this universally recognized test. Such a correlation is developed later in this paper. Water-soluble carbon is in itself a measure of organic material, however, and may be expressed on its own merit.

Filter Characteristics

Because the degree of oxidation of organic material is related to contact opportunity between wastewater and filter biota, tests of residence time within the filter were made by methods developed by Sinkoff *et al.* (10) by using a salt tracer and following conductance versus modal time of appearance in the effluent of the 20-ft deep filter. Results of this analysis may be plotted as a straight line on log-log paper, or as an exponential curve. Figure 2 shows the range of values observed, and may be formulated empirically as

$$T_{sec} = 480 \text{ (mgd/acre)}^{-0.408} \ldots (4)$$

BOD Reduction

BOD reduction versus filter depth and BOD work rates are summarized in Table I and are shown in graphical form for four typical rates in Figure 3. The theoretical considerations of Velz (11) as expanded by Grantham *et al.* (2) were applied to the filter such that fitting of filter data was made by the expression

$$L_D/L = 10^{-KD} \ldots\ldots\ldots (5)$$

where L_D is the remaining BOD fraction, D is depth, K is the reaction rate constant, and L is the removable BOD fraction which may be viewed as a lower limit of the equation.

Values of K and L for the test filter for both BOD extraction and extrac-

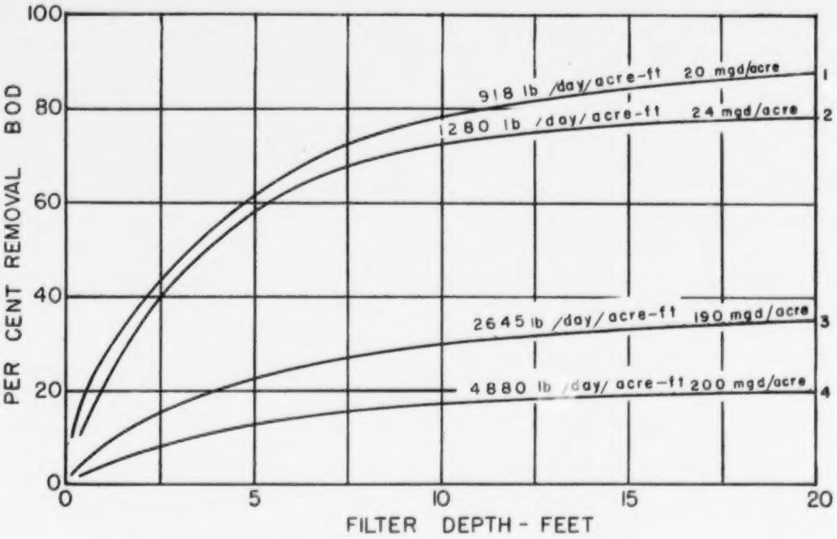

FIGURE 3.—5-Day BOD vs. filter depth.

tion of persulfate oxidized water soluble carbon are given in Table II. Values of K so determined are somewhat smaller than values reported by Grantham *et al.* (2), particularly at the higher hydraulic rates. Values of L are within the reported range. The rate constants K for BOD and water-soluble carbon uptake are related. Data are too meager, however, to draw a definite conclusion.

Good agreement exists between Velz's (11) equation and observed performance in the top 6 to 8 ft of filter at all loading rates and throughout the filter at rates in excess of 1,200 lb of BOD/day/acre-ft. The limiting value of L, however, is reached within the filter bed at rates below 1,200 lb BOD/day/acre-ft, and the equation cannot be used to predict filter performance at all depths. For the case of 24-mgd/acre hydraulic rate and 810 lb BOD/acre-ft/day on a sewage with an initial BOD of 128 mg/l, it was observed that the rate constant K changed with depth and could be approximated by the form

$$K_D = D^{-0.575}/7.0 \ldots\ldots (6)$$

in which K_D is the rate constant at depth D. The resulting expression for

TABLE II.—Selected Filter Loading Data

BOD_5 Loading (lb/day/acre-ft)	Hydraulic Load (mgd/acre)	R/I	Temp. (°F)	BOD (mg/l)		W-S C* (mg/l)		K† (mg/l)		Limit, L† (mg/l)	
				Infl.	Effl.	Infl.	Effl.	BOD	W-S C*	BOD	W-S C*
918	20	1	43	110	11	—	—	0.045	—	0.78	—
1,280	24	1	66	128	22	—	—	0.04	—	0.82	—
2,645	190	1	68	66	37	35	24	0.007	0.006	0.88	0.86
4,880	250	0.5	67	90	64	100	75	0.0025	0.0027	0.86	0.857
1,000	134	4	65	39	16	63	38	0.004	0.005	0.85	0.81

* Water-soluble carbon.
† In $L_D/L = 10^{-KD}$.

the loading rate listed is

$$L_D/L = 10^M \ldots\ldots\ldots (7)$$

in which

$$M = -D^{0.425}/7.0 \ldots\ldots (8)$$

BOD Work Rates

Rate of BOD extraction at various depths is a useful criterion to judge filter performance with depth. The work rate, W_R, in terms of pounds of BOD extracted per acre-foot per day at depths D to $(D + \Delta D)$ may be computed by

$$W_R = (\Delta C/\Delta D)(\text{mgd/acre})(8.33) \ldots (9)$$

in which ΔC is the change in concentration of BOD in depth ΔD at a hydraulic loading rate (mgd/acre).

Observed rates, given in Table I, ranged from 6,600 to 0 lb/day/acre. Actual extraction obtained in any increment of depth may be computed as work W by

$$W = \sum_{D_1}^{D_2} W_R \Delta D \ldots\ldots (10)$$

Values determined for various loading combinations are expressed graphically in Figure 4 in terms of percent-

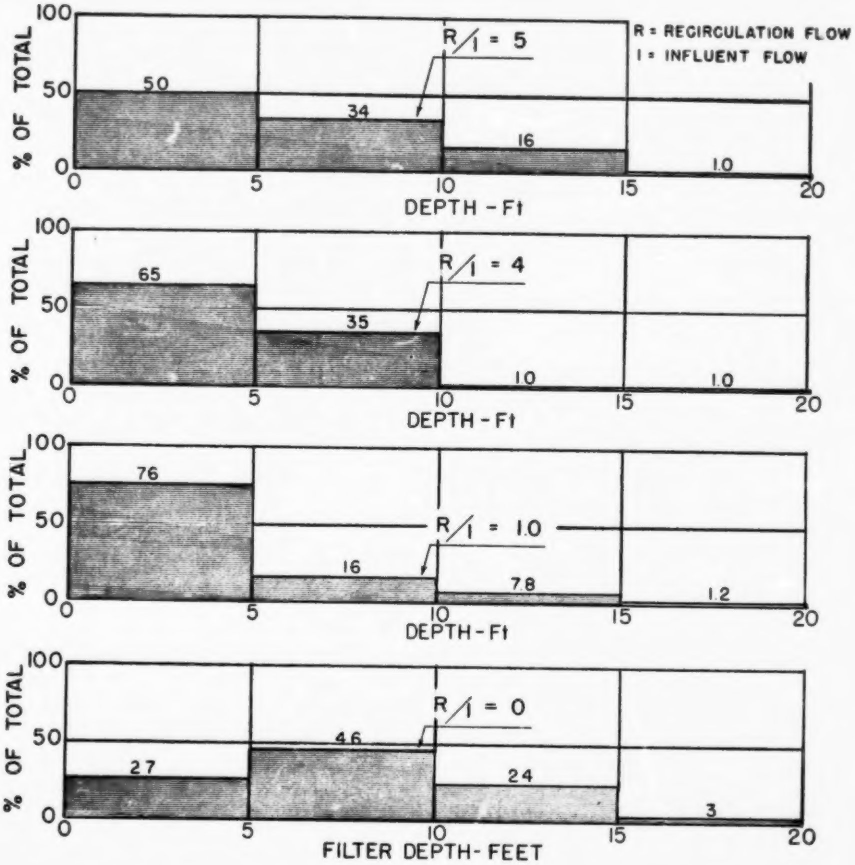

FIGURE 4.—Percentage of total BOD removal per increment of filter depth.

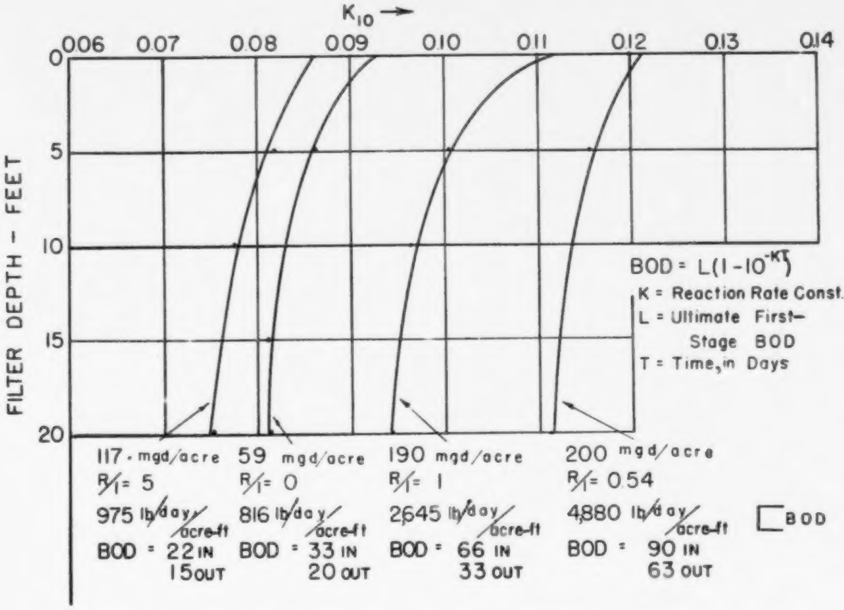

FIGURE 5.—Reaction rate constant, K, vs. filter depth.

age of total work on removal of carbonaceous material as measured by 5-day BOD. Work rates for removal of materials not measured by 5-day BOD are as yet undetermined.

Change in Treatability

As oxidation of organic material proceeds through the filter depth, the more readily available substrates are first removed, followed by material more difficult to oxidize. K-values in the monomolecular reaction as expressed by Equation 2 are indicative of treatability in terms of BOD and were determined with filter depth. Figure 5 shows four such determinations.

Interpretation of true filter efficiency in light of this information presents some provoking thoughts. A comparison of percentage removal of theoretical first-stage BOD L to the removal of 5-day BOD and water-soluble carbon for the cases of the 59- and 117-mgd/acre curves yields the data shown in Table III.

It becomes apparent, therefore, that the criterion of 5-day BOD reduction alone does not give a truly accurate picture. Further study in this biochemical area is needed.

Comparison with NRC Design Formula

Numerous methods are in common usage for the design of trickling filters (11) (12) (13) (14) (15). These vary from theoretical formulations delineating the fundamental laws and for-

TABLE III.—Performance at Two Flow Rates

Flow Rate (mgd/acre)	Removal (%)		
	Theor. First-Stage BOD, L	5-day BOD	Water Soluble Carbon
59	34	39.4	31.4
117	26	31.8	23.3

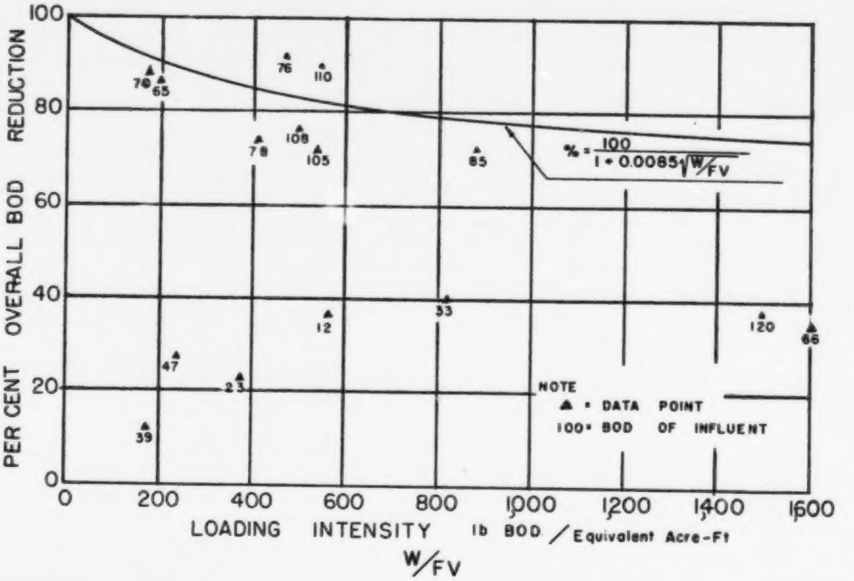

FIGURE 6.—Observed efficiency compared to efficiency computed by NRC formula.

mulas resulting from curve-fitting methods applied to observational data, to application factors (4) of organic and hydraulic loading rates. Among these methods, the National Research Council formulation (15) has been a useful and popular tool.

A comparison between observed ef-

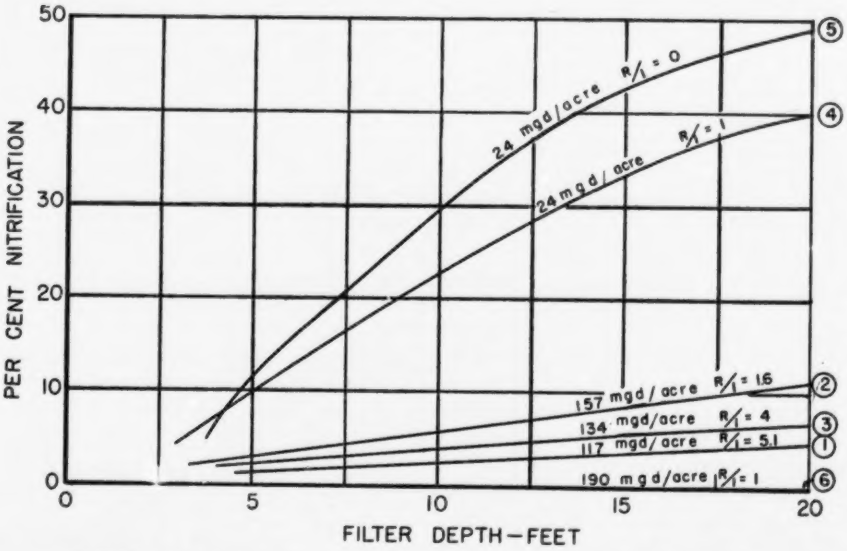

FIGURE 7.—Percentage of nitrification per filter pass vs. filter depth.

TABLE IV.—Nitrification Data*

Curve	Loading Rate		R/I	Lag Depth, a	Rate K_n	Limit N	Initial Nitrogen (mg/l)	Over-all Nitrif. (%)
	(mgd/acre)	(Lb BOD/day/acre-ft)						
1	117	975	5.1	0	0.0014	0.73	7.5	31.5
2	157	1,435	1.6	0	0.003	0.86	7.3	25.5
3	134	1,000	4	0	0.0019	0.87	10.1	20
4	24	810	1	1.5	0.0145	0.95	9.3	49
5	24	900	0	3.0	0.0148	0.97	12.2	48
6	190	2,645	1	—	—	—	9.08	None

* Based on $\frac{N_D}{N} = 10^{-K_n(D-a)}$.

ficiencies and efficiencies computed by the National Research Council formula applied to the filter is shown in Figure 6. Although fair agreement exists at conventional rates involving medium strength sewages, an appreciable error is introduced in those cases where the hydraulic rate is quite high and the sewage applied is relatively weak. This may be interpreted in light of Velz's (11) work as the case of the BOD approaching the limit of the removable fraction. Inadequate contact opportunity and scouring of filter zooglea are possible contributing factors to the low efficiencies at high hydraulic rates, although recent work of Ingram (3) indicates higher hydraulic rates can be employed successfully under controlled conditions.

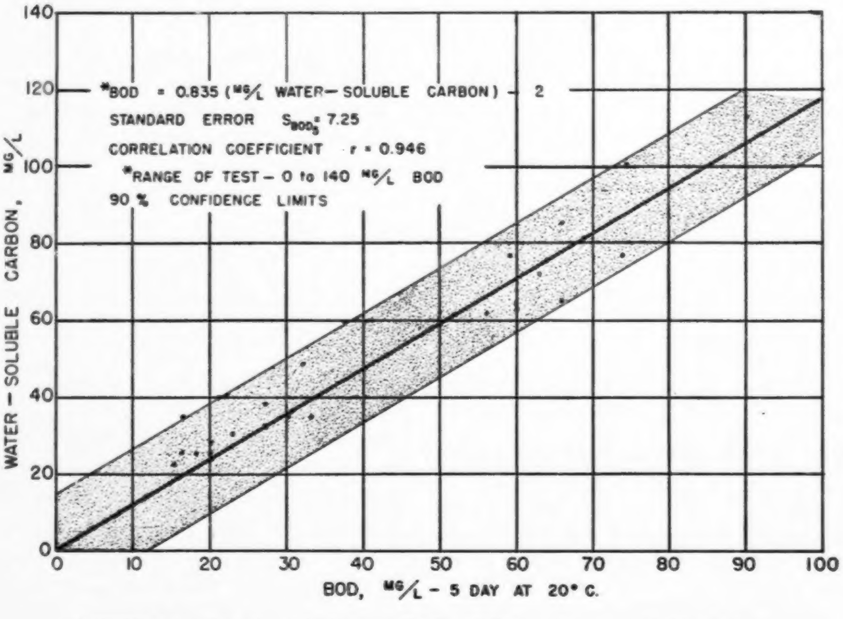

FIGURE 8.—Relationship between 5-day BOD and water-soluble carbon.

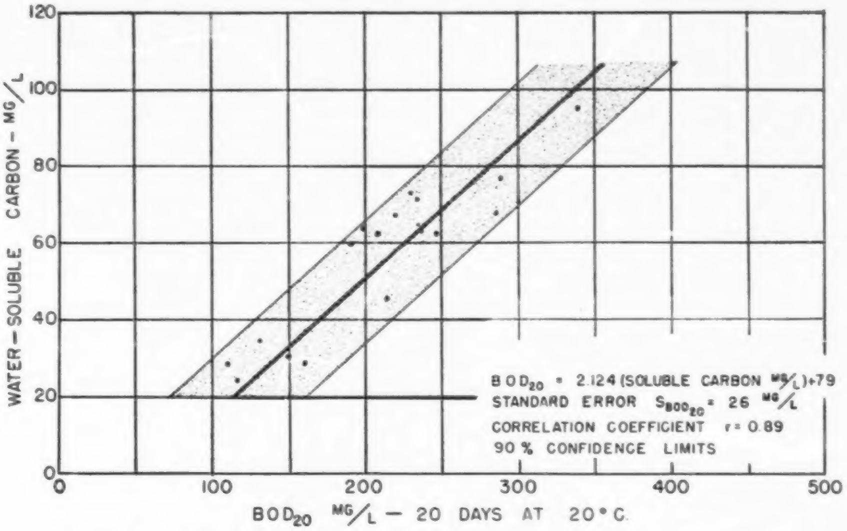

FIGURE 9.—Relationship between 20-day BOD and water-soluble carbon.

Nitrification Observations

Nitrification of applied wastes has been used as a criterion for judging the degree of waste stabilization (7). Therefore, determination of the nitrification ability of the filter was done as an aid to gaining an understanding of depth relationships.

Figure 7 relates per cent nitrification per filter pass to filter depth where per cent nitrification is calculated as the nitrate-nitrogen plus 75 per cent of the nitrite-nitrogen at any level divided by the nitrogen recovered at that level. Equating the nitrification ability of the filter to filter depth was done by the relationship

$$N_D/N = 10^{-K_n(D-a)} \ldots\ldots (11)$$

after Grantham *et al.* (2), where N_D is the oxidizable nitrogen remaining at depth D, N is total oxidizable nitrogen and defines the equation limit, K_n is reaction rate constant, and a is lag depth.

Table IV gives data on values of K_n, limit N, and total nitrification for selected test series.

Persulfate Oxidizable Carbon as an Index of Treatment and Loading

The desirability of being able to determine loading rates and treatment efficiencies in 3 to 4 hr rather than to wait for the conventional 5-day BOD, motivated an investigation of water-soluble carbon as determined by the persulfate oxidation test as an index of treatment. Inasmuch as sanitary engineers and their pollution control standards are oriented strongly toward BOD, a relationship was sought between the two methods, both as a quantitative measure of organic material and as a measure of treatment efficiency.

Figure 8 shows the correlation of 5-day, 20°C, BOD to water-soluble carbon values as determined by persulfate oxidation in the range of 0 to 140 mg/l BOD, and gives 90-per cent confidence limits. Using a method of least squares, a relationship may be written that

$$\text{5-Day BOD} = 0.835\ (\text{mg/l water-soluble carbon}) - 2 \quad \ldots (12)$$

The factor of 2 is a bias observed in favor of carbon, and its significance is not yet determined. The regression coefficient of 0.835 is based on data presented.

The exact interdependence of the BOD reaction constant K of carbonaceous BOD as measured by first-stage ultimate L and sewage characteristics to the water-soluble carbon-BOD relationship are not fully understood and are the subjects of continued research. The correlation coefficient of $r = 0.946$ and the low standard error of 7.25 mg/l, however, indicate that a satisfactory calibration may be made by investigators wishing to use this method. At this state of knowledge, calibration curves should be developed by each investigator on the sewage types encountered.

Long-Term, 20-Day BOD and Water-Soluble Carbon

Because the 20-day BOD measures oxidation requirements of materials other than carbon, it is evident that much variance will be encountered in correlating 20-day BOD to water-soluble carbon. Figure 9 illustrates such data and its 90-per cent confidence limits as determined through a fitting of data by a method of least squares. Although the correlation coefficient of $r = 0.89$ and the standard error of 26 mg/l are not large in view of the normal variance of 20-day BOD, the data are heavily biased in favor of 20-day BOD, and need further study.

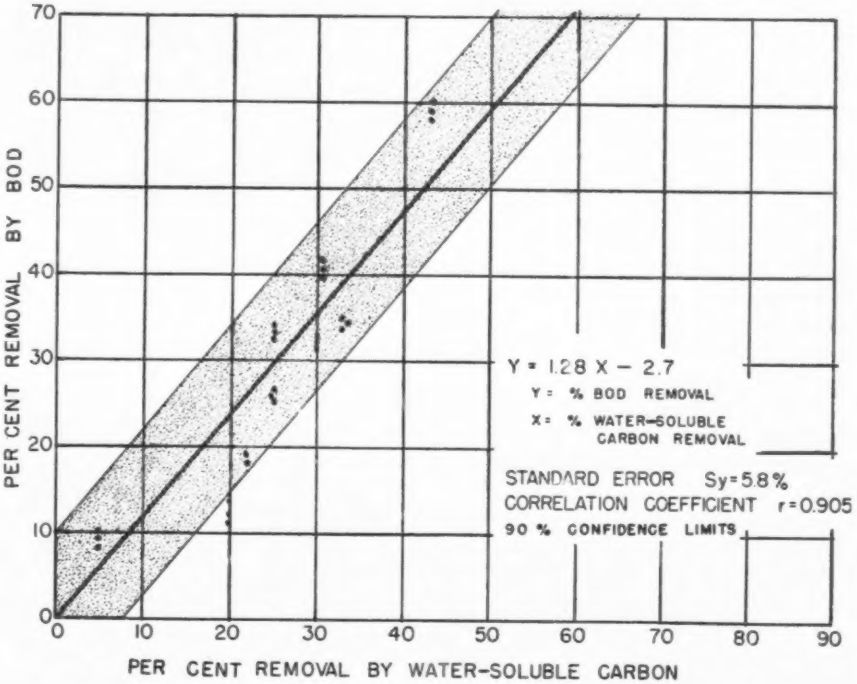

FIGURE 10.—Removal of water-soluble carbon vs. removal of BOD by filter.

Removal Efficiencies by Water-Soluble Carbon and BOD

Because it may be desirable to predict 5-day BOD removal efficiencies by the water-soluble carbon test, a correlation of these parameters was made (Figure 10). A regression analysis by a least squares method yields

$$Y = 1.28X - 2.7 \ldots\ldots (13)$$

where Y is per cent removal based on 5-day BOD, X is per cent removal based on water-soluble carbon, and 2.7 is a biasing factor.

The correlation coefficient of $r = 0.905$ and the standard error of BOD efficiency prediction of 5.8 per cent indicate a correlation within usable limits for the range of data tested.

Conclusions

1. Water-soluble carbon as measured by the persulfate oxidation test is a good measure of organic pollution in water and may be correlated to the 5-day BOD. The exact nature of the total relationship, however, is not completely understood and merits investigation.

2. Information gathered on 5-day BOD reduction and nitrification within the experimental filter substantiates Velz's basic law (11) as expanded by Grantham *et al.* (2). Values of the reaction rate constant K in the expression

$$L_D/L = 10^{-KD} \ldots\ldots\ldots (5)$$

are relatively lower at high organic and hydraulic loading rates involving weak sewage.

3. High hydraulic and organic loadings with the weak sewages examined yielded results far lower than results predicted by theoretical formulas.

4. Oxidation rates with filter depth indicate that test facilities to be constructed with controlled media size and environment need not exceed 8 to 10 ft.

Acknowledgments

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